

# **Annual Report 2016**



# Table of contents

<b>1</b>	<b>INTRODUCTION .....</b>	<b>1</b>
1.1	EXTRA-EUROPEAN DEVELOPMENTS IN 2016 .....	1
1.2	DEVELOPMENTS IN 2016 AT THE EUROPEAN LEVEL .....	1
1.3	DEVELOPMENTS IN SWITZERLAND AND AT THE SWISS PLASMA CENTER .....	2
<b>2</b>	<b>PROGRESS REPORT .....</b>	<b>5</b>
2.1	THE TCV TOKAMAK .....	5
2.1.1	Tokamak physics .....	5
2.1.2	TCV heating systems .....	9
	TCV NBH heating system .....	10
2.1.3	TCV Diagnostics .....	12
2.1.4	Gyrotron physics .....	16
2.2	THEORY .....	16
2.2.1	First principles based simulations of core plasma turbulence .....	18
2.2.3	MHD analysis of tokamak instabilities, 3D magnetic confinement configurations, and interaction with fast particles .....	19
2.2.3	Investigations of the plasma dynamics at the edge of fusion devices .....	21
2.2.4	Modelling in support of experimental activities and real time control .....	21
2.3	BASIC PLASMA PHYSICS .....	22
2.3.1	Interaction of radio-frequency waves with plasma turbulence .....	22
2.3.2	Interaction of suprathermal ions with turbulence .....	23
2.3.3	Diagnostics development to investigate three-dimensional blob physics .....	24
2.3.4	Plasma Applications .....	25
2.3.5	Flat inductive plasma for large area plasma processing and theory .....	25
2.3.6	Gas breakdown investigation and mitigation in complex geometries .....	26
2.3.7	Helicon plasma source for negative ions production .....	27
2.4	SUPERCONDUCTIVITY .....	28
2.4.1	Superconducting Magnets for DEMO .....	28
2.4.2	Development of high field insert coil made of HTS tapes .....	28
2.4.3	EDIPO test facility .....	29
2.4.4	Non-destructive methods for ITER joints .....	29
2.4.5	Test of HTS dipole inserts for CERN .....	29
2.4.6	Tests of superconductors for ITER in SULTAN .....	30
2.5	INTERNATIONAL AND NATIONAL ACTIVITIES .....	30
2.5.1	Gyrotron development for ITER .....	30
2.5.2	EC Upper Launcher (UL) development for ITER .....	31
2.5.3	ITERIS: Design and first applications of the ITER Integrated Modelling & Analysis Suite (IMAS) .....	32
2.5.4	Work package Heating and Current Drive (WPHCD) in the frame of EUROfusion .....	32
2.5.5	Work package Plant level System Engineering, Design Integration and Physics Integration (WPPMI) in the frame of EUROfusion .....	33
2.5.6	Contribution to the scientific exploitation of JET .....	33
2.5.7	Contribution to the scientific exploitation of Asdex-Upgrade .....	34
2.5.8	Work package Divertor Tokamak Test Facility (WPD TT1) in the frame of EUROfusion .....	34
2.5.9	Plasma surface interactions in collaboration with the University of Basel .....	35
<b>3</b>	<b>THE EDUCATIONAL ROLE OF THE SPC .....</b>	<b>37</b>
3.1	BACHELOR COURSES GIVEN BY SPC STAFF .....	37
3.2	MASTER COURSES AND LABORATORY GIVEN BY SPC STAFF .....	38
3.3	POSTGRADUATE COURSES GIVEN BY SPC STAFF .....	39
3.4	DOCTORATE DEGREES AWARDED DURING 2016 .....	40
3.5	PH.D. THESES SUPERVISED BY SPC STAFF ONGOING AT THE END OF 2016 .....	43
<b>4</b>	<b>COMMUNICATION ACTIVITIES IN 2016 .....</b>	<b>50</b>

<b>5 FUSION &amp; INDUSTRY RELATION.....</b>	<b>51</b>
<b>APPENDICES.....</b>	<b>52</b>
APPENDIX A ARTICLES PUBLISHED IN REFEREED SCIENTIFIC REVIEWS DURING 2016 .....	52
APPENDIX B CONFERENCES AND SEMINARS .....	61
<i>B.1 Conference and conference Proceedings published in 2016 .....</i>	<i>61</i>
<i>B.2 Seminars presented at the SPC in 2016 .....</i>	<i>63</i>
APPENDIX C EXTERNAL ACTIVITIES OF SPC STAFF DURING 2016 .....	66
<i>C.1 National and international committees and ad-hoc groups .....</i>	<i>66</i>
<i>C.2 Editorial and society boards .....</i>	<i>67</i>
<i>C.3 EPFL committees and commissions .....</i>	<i>67</i>
<i>C.4 EUROfusion Task Force leaders and Project Leaders .....</i>	<i>68</i>
APPENDIX D THE BASIS OF CONTROLLED FUSION.....	69
<i>D.1 Fusion as a sustainable energy source .....</i>	<i>69</i>
<i>D.2 Attractiveness of fusion as an energy source .....</i>	<i>70</i>
APPENDIX E SOURCES OF FINANCIAL SUPPORT .....	71

# 1 INTRODUCTION

## *1.1 Extra-European developments in 2016*

In 2016 a new project baseline plan for the ITER project has been developed by the ITER International Organization. The revised schedule, accepted by all parties in November 2016, foresees the first ITER plasma by the end of 2025, an ambitious, success-based, yet credible target. This now represents the reference point for the accompanying programmes around the world, whose aim is to maximize ITER's chances of success, as well as for the developments in view of DEMO, the step that will prove that a commercial deployment of fusion energy is possible.

Much progress has been achieved in 2016 both on the ITER site, for example with the construction of the tokamak assembly hall, and in the manufacturing of key components by the various domestic agencies, such as a section of the superconducting coil for the generation of the toroidal magnetic field, of 17m of height and more than 300tons of weight.

The arrival in Naka, Japan, of the first toroidal magnetic field coil for the JT-60SA tokamak from Europe stands out as a milestone in the final phase of the construction of the device as well as for the significant contribution of Europe to this large-scale project.

The increased focus of the international community towards the final stages of the ITER construction and the conceptual design activities for DEMO was evident from the contributions presented by researchers from all over the world at the 26<sup>th</sup> IAEA Fusion Energy Conference (FEC) in Kyoto, Japan, in October. A number of new fusion concepts were also discussed there, with a notable participation of private investors in different countries, a proof of the increasing appreciation of the potential of fusion as a source of clean and sustainable energy for the future.

## *1.2 Developments in 2016 at the European level*

Fusion in Europe is conducted under the auspices of the EUROfusion Consortium, within the 8<sup>th</sup> EU Framework Program on Research and Innovation, known as Horizon 2020. The guiding principles of the EUROfusion programme are defined in the document "EFDA Roadmap to the realization of fusion energy", aimed at obtaining production of electricity by a fusion reactor by the second half of the century. In connection with the EUROfusion mid-term review, an important exercise has been started this year at the European level to update and adapt the Roadmap in view of the new ITER timeline and of the progress that is continuously achieved in the international fusion community.

The EUROfusion work programme is organized into two departments, one focused on ITER physics, the other on DEMO developments, referred to as Power Plant Physics and Technology. In addition to JET, a crucial work package in the ITER Physics Department is dedicated to experimentation on the three medium size tokamaks (MSTs) that are judged essential for the realization of the Roadmap goals, ASDEX-Upgrade (IPP – Germany), MAST (CCFE – UK), and TCV (EPFL – Switzerland).

In 2016, ASDEX-Upgrade and TCV were fully operational at the same time, and conducted complementary extensive experimental campaigns, together with JET. The JET experiments focussed on the effects of the ITER like wall, made of a combination of Beryllium and Tungsten, on the Tritium retention and the plasma performance, and other crucial aspects for ITER operation, such as the mitigation of disruptions. Synergies in the MST approach, and the added value of developing a coordinated scientific programme were evident for the first time this year, with many high-impact MST joint contributions to the IAEA FEC conference.

The Roadmap revision is showing the increasing importance of addressing the issue of the plasma exhaust, i.e. of how to efficiently extract heat and particles from the tokamak plasma without affecting the core fusion performance and the integrity of the plasma-facing components. For this, a call for proposals to upgrade existing machines and adapt them to specific plasma exhaust studies has been launched by EUROfusion in 2016. All three MSTs have responded to this call.

The year 2016 was special for the community involved in the stellarator line of research. After the first hydrogen plasma discharge, obtained in Wendelstein 7-X just before the end of 2015, helium plasmas were produced for the first time in 2016, in the presence of the German Federal Chancellor, and Electron Cyclotron heated plasmas were successfully investigated.

Following five years of successful operation, the HELIOS IFERC-CSC computing facility dedicated to European and Japanese fusion research, in Rokkasho, Japan, has been terminated in 2016. A new supercomputer facility named MARCONI, dedicated to fusion research in Europe and supported by EUROfusion, has been established. It is operated by CINECA in Bologna, Italy, prolonging the access of European and Swiss fusion researchers to a state-of-the-art high performance computing platform. Researchers of the Swiss Plasma Center, together with European colleagues, in addition to having access to MARCONI, have gained some of the largest allocations of resources on the PIZ DAINTE platform of the Swiss National Supercomputing Centre (CSCS), which is the most powerful supercomputer in Europe.

The completion of ITER remains the main priority of the European fusion programme. Europe bears by far the largest share of ITER construction costs and is responsible for crucial elements of the project, such as the tokamak vacuum vessel and the civil engineering infrastructure. The European participation to ITER is under the responsibility of the European Joint Undertaking for ITER and the Development of Fusion Energy, known as Fusion for Energy (F4E), in Barcelona. Stronger collaborations and synergies have been established in 2016 between F4E and the ITER Organization, with in particular the development on the F4E side of a counterpart of the new ITER baseline, a plan referred as *straight road to first plasma*, aimed at optimizing the path to the end of the ITER construction and the first plasma experiments.

### ***1.3 Developments in Switzerland and at the Swiss Plasma Center***

On the political level, the continuation of the participation of Switzerland to the EURATOM and the European domestic agency F4E activities beyond January 2017 was subject to the ratification from Switzerland of the extension of the free

circulation of people in Europe to Croatia. Such ratification, which was needed by February 9, 2017, already came in December 2016. Since January 2017 Switzerland is therefore again fully associated to the framework programme Horizon 2020.

The Swiss Plasma Center, created in September 2015, follows up the mission of the Center for Research in Plasma Physics (CRPP) and is reinforcing the international aura and impact of Switzerland in plasma and fusion research. At its two sites, the EPFL and the Paul Scherrer Institute (PSI), the Swiss Plasma Center, contributes significantly to many of the scientific and technological activities of the EUROfusion consortium, as well as in the ITER project, both directly and through F4E.

The state-of-the-art infrastructures that are currently developed, and will be improved in the 2017-2020 period, focusing primarily on fusion energy research, enable EPFL to fulfill, in the frame of the Association of Switzerland with Horizon 2020-Euratom, its role and obligations in the broader context of Europe, Euratom and ITER on the way to fusion energy. These developments are facilitated by an *ad hoc* financial support of 10MCHF granted in 2015 by the ETH Board. These funds will be deployed to further enhance the capabilities of the TCV tokamak to investigate crucial issues for ITER, DEMO and the future commercial reactors, as well as for expanding activities in space plasmas, astrophysics and in applications of plasmas to society and industry.

An important element of the TCV upgrade plan is the construction of an in-vessel structure, with mechanical baffles, several gas injection valves and a cryo-pumping system. This would create a divertor volume of variable closure with a high degree of control of the plasma and neutral gas conditions, for the investigation of important aspects of the plasma exhaust issue, in conventional, i.e. ITER-like, and innovative magnetic configurations, potentially applicable to DEMO. Such research and hardware development plans are fully in line with the EUROfusion strategy for innovation in the plasma exhaust area, hence are likely to also obtain European scientific, technical and financial support.

The divertor upgrade will also capitalise on the installation of additional plasma heating systems on TCV. The heating upgrade is conducted in two steps, one essentially completed in 2016 and another foreseen in 2017-2020. The first step includes the installation of a 1MW 15-30keV Neutral Beam Injector (NBI), mainly used for heating the ions of the plasma, and the acquisition of two 0.75MW gyrotron microwave sources, mainly used for heating the electrons of the plasma and driving plasma current, at the 2<sup>nd</sup> harmonic, i.e. at 87GHz. The second step consists of a 1MW, 50 keV Neutral Beam, for addressing burning plasma physics issues, in particular plasma rotation and fast ion interactions with static and dynamic fields, and two 1MW dual-frequency gyrotrons, at 83GHz and 126GHz, thus able to operate at 2<sup>nd</sup> or 3<sup>rd</sup> harmonic. The development of these two gyrotrons, in the frame of a contract with TED, France, has significantly progressed in 2016.

In 2016, the Swiss Plasma Center has operated the TCV tokamak practically continuously, in an extremely intense experimental campaign, made of two parts: one conducted and financially supported in the international frame of the MST EUROfusion work package, and one on its own scientific priorities, providing the data necessary for successfully completing several PhD theses. For the former, more than one thousand successful plasma discharges were delivered for a scientific programme conducted jointly with a number of scientists from all over Europe and overseas. These collaborators have temporarily increase the team by at least a factor of two. The plasma ions have been heated directly for the first time in several experiments with the recently installed NBI system.

Beyond TCV, research at the EPFL site includes basic plasma physics investigations on the TORPEX device, theory and numerical simulations, plasma heating and current drive technology. For the latter, a new framework contract has been signed with the ITER Organization for the setting and operation of a facility, named FALCON, for the testing of microwave components for ITER originating from Europe and other ITER parties.

The PSI site hosts the applied superconductivity group of the Swiss Plasma Center, which is completing the qualification of the ITER conductors in the frame of a large contract with the ITER International Organization, and investigates aspects of DEMO magnets, including high temperature superconductors, in collaboration with the EUROfusion Power Plant Physics and Technology department. As an example of the extension of the Swiss Plasma Center beyond fusion, the know how of the group has recently been applied to the design of magnets for particle accelerators (the CERN Future Circular Collider), and medical applications. These partnerships may also prove essential in the reconstruction of an upgraded version of the coil of the EDIPO facility, which was damaged irreversibly in the course of the year.

The Swiss Plasma Center also participates to experiments on JET. Two members of the Swiss Plasma Center act as Project Leaders and one as Deputy Project Leader of EUROfusion work packages. Moreover, the Swiss Plasma Center is leading two Enabling Research projects, the more academically oriented projects of the EUROfusion consortium.

Several projects were accomplished successfully in 2016 in the vast area of plasma applications, in collaboration with various industrial partners and research organizations. A notable example is provided by the development and optimization of helicon wave plasma sources, conducted in collaboration with Helyssen, a spin-off company of the Swiss Plasma Center. These sources are used for a wide variety of applications, from food packaging to the production of high density uniform plasma columns for more efficient plasma sources for DEMO neutral beams and for plasma wave-field accelerator concepts, for which a collaboration with CERN is active.

At EPFL, the Swiss Plasma Center has maintained its attachment to the physics community, through its affiliation with the newly created Institute of Physics, yet reporting directly to the Dean of the Basic Science Faculty. Important events in the academic life of the Center in 2016 have been the nomination to Associate Professor with tenure of Paolo Ricci, head of the theory group, and that of Christian Theiler as Tenure Track Assistant Professor in Physics. The position of Prof. Theiler, whose activities are focused in the area of the plasma exhaust, had been opened in conjunction with the retirement of Prof. Minh Quang Tran, former CRPP Director, though Prof. Tran will continue to contribute to the activities of the Center and EUROfusion as leader of the DEMO Heating and Current Drive project.

The Swiss Plasma Center keeps playing a crucial role in education and training, with 37 PhD students active at the end of 2016. It offers many courses at different levels on plasma physics, fusion, and related technologies, at EPFL and in the context of the European wide education initiative Fusenet. In 2016, the second and third editions of a Massive Open Online Course on Plasma Physics and Applications, offered on the basis of the EdX platform, have led to a total number of enrolments in this course exceeding 10'000.



## 2 PROGRESS REPORT

### 2.1 *The TCV tokamak*

#### 2.1.1 *Tokamak physics*

The TCV tokamak was in operation almost continuously during 2016, in a considerably updated setup, including its first (1MW) neutral beam injector, two new 0.75MW gyrotrons for Electron Cyclotron Resonance Heating (ECRH), and significant modifications and upgrades to diagnostics and to the facility infrastructure. After the restart in late 2015, the 2016 campaign was characterized by ever-increasing efficiency, measured in shots per day (routinely over 35, peaking at 45) and in the rate of successful shots - with all technical requirements met - well above 60% in the second half of the year. This was also the first campaign (including the late-2015 restart) in which TCV was partly run as a European facility under the auspices of the Medium-Size Tokamak (MST) Task Force within the EUROfusion consortium. This was a highly successful campaign, with a total of 1213 successful shots delivered to the scientific programme. During 2016 alone, 1877 shots (of which 1030 successful) were run for EUROfusion and 1772 (of which 1133 successful) for the internal programme of SPC. The latter, which remains open to international collaborations, is the primary outlet for Ph.D. thesis work, a fundamental component of our mission as an academic institution.

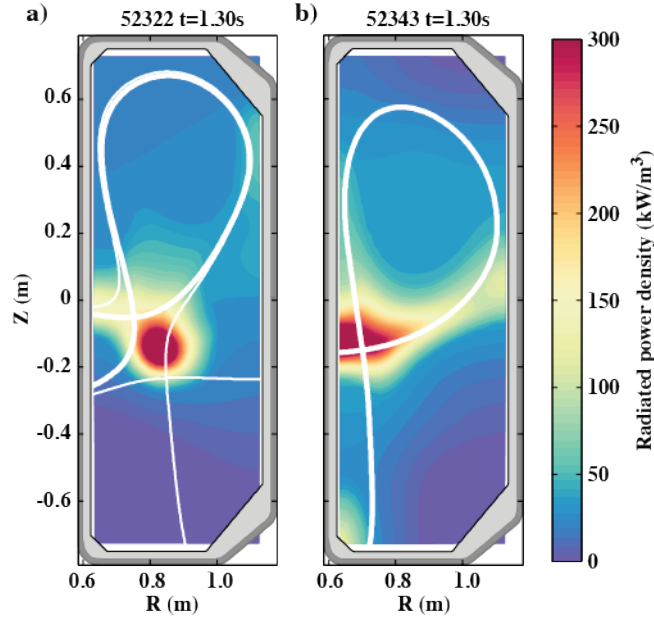
Preparations have also begun in earnest for extensive further upgrades to our heating systems (an additional 1MW neutral beam and two additional dual-frequency 1MW gyrotrons, to be added in the next two years) and to the vacuum vessel, which will be fitted by 2019-2020 with modular and removable divertor baffles of varying sizes and possibly with a cryopump and additional divertor coils, primarily to study advanced divertor configurations in reactor-relevant conditions.

With Neutral Beam Heating (NBH), central (carbon) ion temperatures in excess of 2.5keV and toroidal rotation velocities of 250km/s have been obtained, both well above any previous TCV values (<1keV and 30km/s intrinsic rotation). Initial experiments were carried out to compare on-axis and off-axis co-injected NBH with the aid of modeling. Fairly high losses in the beam duct (~10%), from shine-through (~20%), and from loss orbits (~10%) have to be assumed for the simulations to produce fast-ion densities consistent with measurements. A loop voltage drop is clearly detected at the NBH onset, demonstrating net current drive from beam ions.

In the area of ITER scenario development, an experiment was carried out in conjunction with JET and MAST to explore alternative paths to high H-mode (High confinement mode) pedestal pressure in cases of higher collisionality and reduced edge bootstrap current. Theory suggests that a stable path may be charted to the target pressure by overshooting it, i.e., increasing the plasma pressure in L-mode (Low confinement mode) beyond the target value, before the transition to H-mode. The strategy was to increase the L-mode performance in a single-null diverted plasma with unfavorable ion  $\nabla B$  drift and then rapidly activate the opposite X-point to induce the L-H transition. The ballooning stabilization results in a lower Edge Localized Mode (ELM) frequency, which in turn acts to increase the pedestal

pressure further: a higher stored energy – by up to 50% – is then observed to last through several ELM cycles.

Investigations into the physics of plasma exhaust and detachment have been conducted over multiple fronts, in a wide variety of divertor configurations. The conventional single-null (SN) was investigated with varying poloidal or total flux expansion. A particular form of poloidal flux expansion is poloidal flux *flaring* near the target, resulting in a configuration termed ‘X divertor’. When total flux expansion is achieved by moving the target to a larger major radius, one speaks of ‘super-X divertor’. The ‘snowflake’ divertor, characterized by two closely spaced X-points, has also been extensively studied, in the two known variants defined by whether the secondary X-point is in the private (SF+) or common (SF-) flux region, the latter case further categorized as high-field-side (HFS) or low-field-side (LFS) SF- depending on the secondary X-point location. The X-point-target divertor – also realized in TCV – is topologically akin to the LFS SF-, with the secondary X-point close to the target.



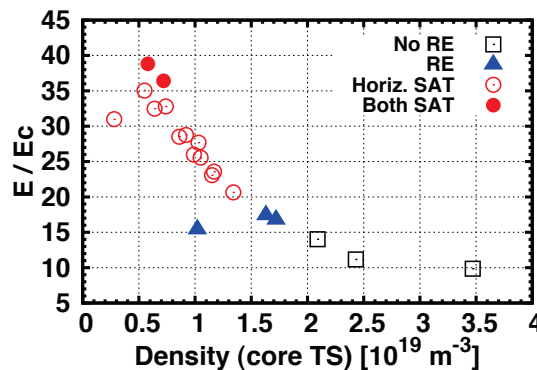
**Fig. 2.1.1** Radiated power density in  $N_2$  seeding experiments in (a) snowflake minus and (b) single-null configurations for the same density ( $\langle n_e \rangle = 4.0 \times 10^{19} \text{ m}^{-3}$ ) and seeding rate ( $\Gamma_{N_2} = 2.8 \times 10^{20} \text{ molecules/s}$ ).

All the detachment experiments were performed in Ohmic L-mode plasmas with the VB drift in the unfavourable direction for H-mode, which is known to facilitate detachment. The C III and D $\alpha$  radiation fronts are seen to move towards the X-point well before detachment, though substantial radiation continues to be emitted from the outer leg at the roll-over time. After the onset of detachment, a gradual broadening or “shoulder” is generally seen to form in the upstream SOL density profile. In the conventional SN scenario, the detachment dynamics appear to be broadly unaffected by variations in fueling and wall gap. Poloidal flux expansion (varied in TCV by over a factor 4) automatically increases the wetted area, the connection length, the divertor volume, and the divertor leg width. No change in detachment threshold, however, is detected during the flux variation. Similar observations are made in the X-divertor case, i.e. with an increase in flux-surface *flaring* near the target. A variation of the connection length can also be obtained in TCV without changes in flux by varying the vertical plasma position: the threshold

density is found to decrease and the depth of detachment (ion flux drop) to increase with increasing leg length in this case. In the snowflake scenario, nitrogen seeding was applied to a LFS SF- plasma to test the specific prediction by EMC3-EIRENE of an enhanced impurity radiation region between the two X-points, which was indeed confirmed (Fig. 2.1.1).

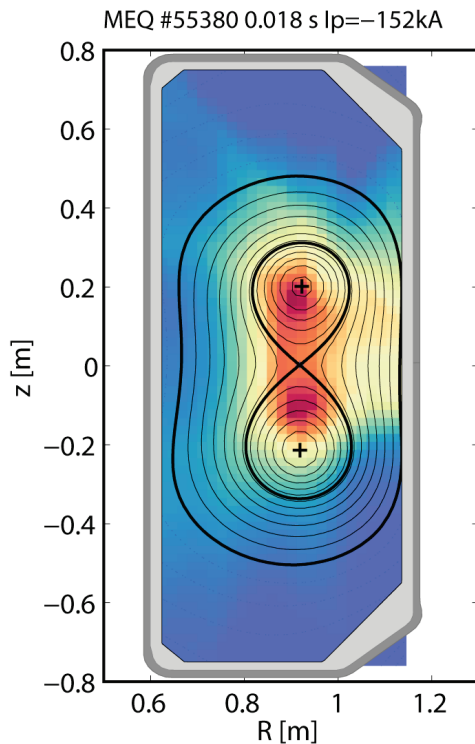
A study of the scaling of the SOL power decay length,  $\lambda_q$ , and spreading factor,  $S$ , on the divertor leg length was undertaken to contribute to a multi-device database. While  $\lambda_q$  increases with the leg length, no clear trend is detected for  $S$ . The hypothesis that  $\lambda_q$  is determined by upstream transport features and is unaffected by plasma and divertor geometry is strongly put into question by these results. The in-out  $\lambda_q$  asymmetry observed earlier in AUG was also explored, with varying upper triangularity (from positive to negative), varying field direction and both D and He as main plasma species. The well-known “narrow feature” in the SOL enhancing the heat flux in the limited L-mode regime was found for the first time to disappear at low current or high density. The SOL density profile broadening discussed earlier is in fact observed also in the absence of detachment with favourable ion VB drift. The possible connection with blob dynamics was explored with a connection-length scan: while the density broadening correlates with larger blob size, no dependence is found on the connection length itself.

Research on disruption and runaway electrons has received considerable impetus in 2016. Disruption mitigation by ECCD was explored with deposition scans around the  $q=2$  surface, revealing a narrow optimum. Runaway electron (RE) experiments were performed in circular Ohmic L-mode plasmas. A stationary RE beam is generated in the quiescent, non-disruptive phase when the line-averaged density lies below  $3 \cdot 10^{19} \text{m}^{-3}$  and the toroidal electric field normalized to the critical field exceeds 15 (Fig. 2.1.2). Runaway mitigation was attempted with only partial success: both Ne and Ar injection lead to increased dissipation but not to total suppression, arguably because of insufficient throughput. In the disruptive phase, robust RE beams are generated with pre-disruption line-averaged densities below  $2.5 \cdot 10^{18} \text{m}^{-3}$ . Full current replacement by REs can be obtained, yielding seemingly pure RE-beam discharges lasting up to 650ms. Explicit mitigation was also investigated, by controlling the Ohmic transformer primary to induce a controlled shutdown. Termination of the RE beam over a range of total current values was demonstrated successfully, suggesting in particular the importance of minimizing the loop voltage to avoid deleterious bursts of MHD activity.



**Fig. 2.1.2** Classification of runaway-electron discharges vs central density and normalized toroidal electric field, based on signals from heavily shielded hard-X-ray detectors: no RE = no signal, RE = finite signal, Horiz. SAT = midplane detector saturated, Both SAT = midplane and top detectors saturated.

In the area of real-time control, an important development was the commissioning of a new, generalized position and shape controller, based on boundary flux errors and on a flexible, SVD-based approach to assign preferential weighting to physically meaningful quantities based on specific research goals. A new real-time MHD mode analysis technique has also been successfully tested. This employs a dedicated node to calculate the SVD of the fast magnetic probe signals, the principal axes of which are then compared with markers computed from synthetic signals generated by a theoretical model of rotating modes. Various controllers for the plasma  $\beta$  and density and  $q$  profiles have been developed within the environment of the real-time control-oriented tokamak profile simulator RAPTOR, using approaches such as adaptive control or model-based predictive control, and have been tested successfully on TCV. A dedicated effort is underway to develop the know-how for the integration of multiple controllers that will be necessary in a reactor. In the 2016 TCV campaign, the new shape controller, a model-predictive controller for both  $\beta$  and the  $q$  profile, a model-based robust density controller, and an NTM controller were demonstrated to operate simultaneously. NTM control by ECRH – as well as NTM triggering – in particular was explored in great detail through systematic scans of plasma and ECRH parameters.



**Fig. 2.1.3** *Doublet: magnetic equilibrium reconstruction and soft X-ray tomographic inversion.*

After early attempts in the Doublet devices at General Atomics, TCV has long been seen as the optimal machine in which to attempt to develop the doublet configuration, characterized by two plasmas with a common X-point. This scenario holds the promise of achieving higher confinement and density with highly increased effective elongation. Thanks to careful tuning of a double breakdown and discharge start-up, in feedforward mode, a doublet discharge has been sustained for the first time for up to 20ms at a peak current of 260kA (Fig. 2.1.3). While this scenario is reproducible, it is not yet understood why the discharge eventually collapses.

Fundamental explorations of ECRH physics have long been a part of the TCV programme. In 2016, the interaction of vertically-launched third-harmonic waves with the plasma was characterized for the first time using a transmission diagnostic in simply magnetized plasmas with no toroidal current. The eventual goal is to study the effect of turbulence and blobs on wave propagation.

Direct characterization of plasma turbulence has also continued, with strong developments particularly in the study of the geodesic acoustic mode, which has now been measured for the first time by SOL diagnostics such as Langmuir probes and infrared cameras, revealing complex dynamics particularly in diverted plasmas, which point to particle flux being modulated by the GAM, as suggested earlier by theory.

Wall conditioning with second-harmonic ECRH in He was explored in TCV in specific support of JT-60SA, whose permanent magnetic field will preclude more conventional techniques such as glow-discharge cleaning. In addition to the main toroidal field, poloidal fields were applied and tuned to maximize the discharge homogeneity and wall coverage, the optimum field amplitude being  $\sim 0.1$ - $0.6\%$  of the toroidal field. The ECRH power used scales to 1-5MW for JT-60SA by wall surface area. Conditioning was demonstrated by a successful ensuing standard D2 plasma breakdown.

### ***2.1.2 TCV heating systems***

#### ***TCV ECH/ECCD system***

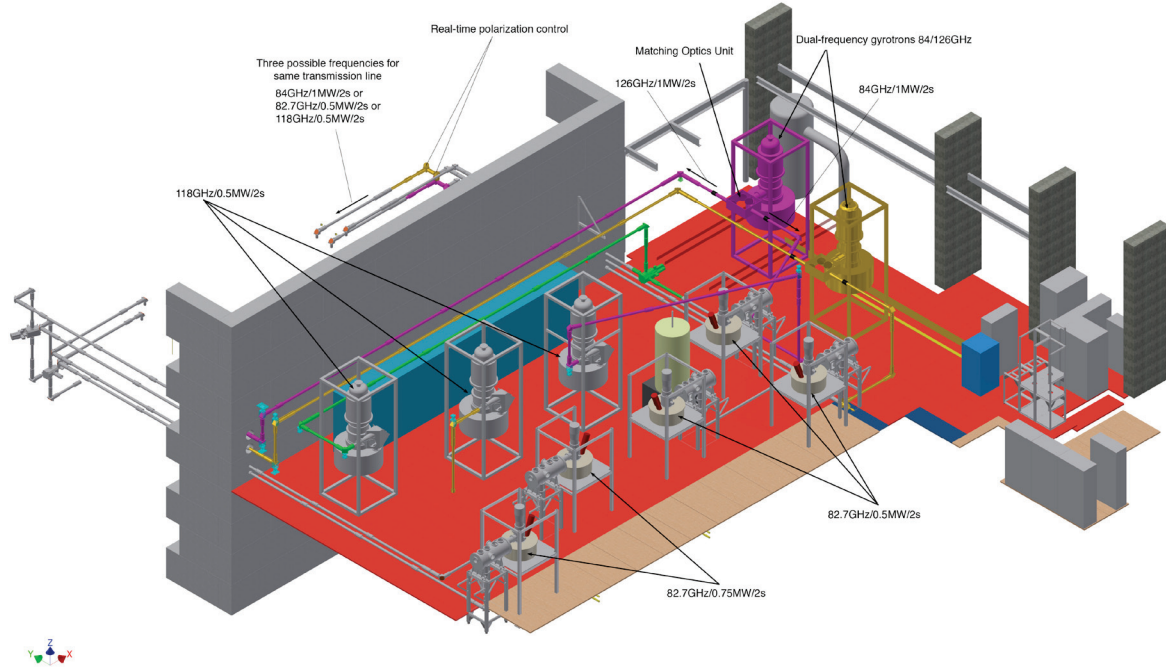
The Electron Cyclotron (EC) system on TCV, has been upgraded in 2016 with two new gyrotrons (82.6GHz, 0.75MW/each, 2s) in replacement of three old gyrotrons (82.6GHz, 0.5MW/each, 2s) which, after nearly 20 years of operation, cannot be repaired anymore. With these new gyrotrons, the EC-system on TCV presently consists of 5 gyrotrons used for second harmonic X-mode (X2) heating (ECRH) and/or current drive (ECCD) experiments with a total available power at 82.6GHz of 2.75MW and 3 gyrotrons used for X3-ECRH with a total available power of 1.25MW at 118GHz. The EC-system in its present configuration has been extensively used during the MST1 2016 campaign.

#### ***Upgrade of the EC system with two dual-frequency gyrotrons***

The upgrade of the EC-system of the TCV tokamak with the two MW-class dual-frequency gyrotrons has entered in its realization phase. The dual-frequency gyrotrons (84 or 126GHz/2s/1MW) are being manufactured by Thales Electron Devices with the first one foreseen to be delivered at SPC by the end of November 2017. In parallel to these developments, all the auxiliaries needed for operating the gyrotrons and efficiently transmitting the RF power to the plasma have been designed. For some auxiliaries such as the superconducting magnets, high-voltage power supplies and RF loads, a number of contracts have been put in place. For extending the level of operational flexibility of the TCV EC-system, the integration of the dual-frequency gyrotrons adds a significant complexity in the evacuated 63.5mm-diameter HE<sub>11</sub> transmission line system connected to the various TCV low-field side and top launchers. In collaboration with CNR-Milano, an optimized



solution has been designed which includes some high-power evacuated quasi-optical systems (Matching Optic Units) that will be eventually manufactured at SPC. The present EC-system with the addition of the two dual-frequency gyrotrons integrated with new transmission lines is shown in Fig. 2.1.4.



**Fig. 2.1.4** *TCV EC-system including two additional dual-frequency gyrotrons. Depending on the frequency generated (126 or 84GHz), the mm-wave radiation is directed via high-power switches towards the corresponding existing transmission lines for top-launch (X3@126GHz) or low-field-side launch (X2@82.7/84GHz or X3@118GHz). The real-time polarization control will be made by polarizers placed in the mitre bends as foreseen in the ITER transmission lines.*

### **TCV NBH heating system**

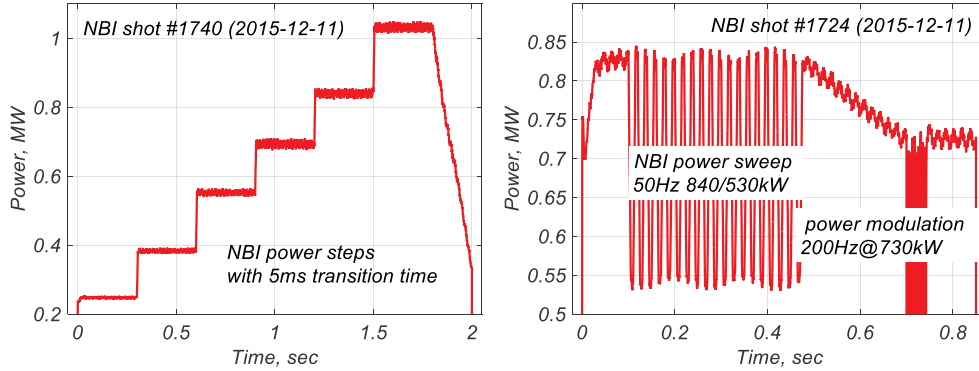
2016 saw the installation and operation of the first Neutral Beam for Heating (NBH) on TCV. This beam was scoped at a nominal power of 1MW of 25keV neutrals. Although beam delivery was late, installation of the beam itself together with the power supply units was successful before the MST (EuroFusion collaboration on Medium-Sized Tokamaks) campaign commenced.

The heating beam itself, together with the vacuum, cryogenic and power supply systems have proven reliable but the beam geometry itself and the calorimeter assembly, placed between the beam and TCV, remain problematic. Initial estimations with nominal beam divergence indicated that heating of the beam duct between the NBH and TCV would be tolerable. A few incidents occurred, where parts of this system melted, resulting in a vacuum/cooling-water failures, and the calorimeter mechanics indicated that the beam was wider than planned. Extra cooling was installed on the NBH to TCV duct and several thermocouples monitor the duct in-shot and between-shot temperature. In general, until the beam reaches

specifications, it was decided to limit the injected energy to 500kJ per plasma discharge.

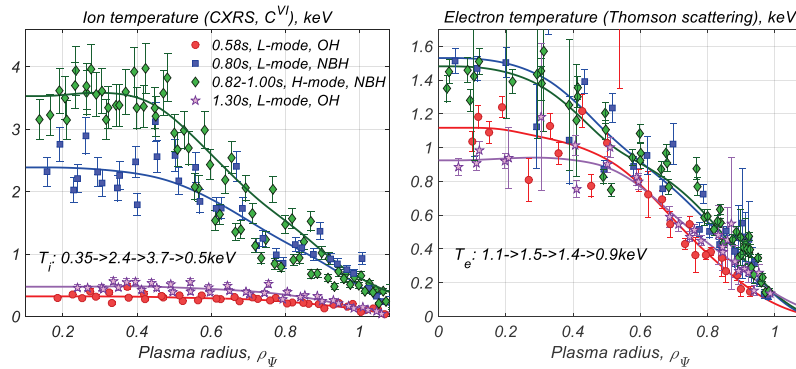
Nevertheless, NBH was, for the first time on TCV available for the entire MST campaign, albeit at this reduced injected energy. The complete beam system from power supply to neutral beam was extremely reliable, with a total of 702 successful shots.

One of the design criteria of the beam was the possibility of complex beam modulation and continuous power variation. This has worked well, and Fig. 2.1.5 shows example discharges with a stepped NBH power and with strong modulation.



**Fig. 2.1.5** NBI power steps and modulation during NBI commissioning on the TCV

The ability to directly heat the plasma ions complements the strong ECH electron heating programme described above. Many experiments from plasma heating, plasma bulk rotation to completely new subjects such as the slowing down time of beam ions in the plasma (simulating fusion alpha particles) were initiated. As an example, Fig. 2.1.6 shows the electron and ion temperature evolutions for a discharge with full NBH power where the measured ion temperature now attained values  $\sim 2\times$  the electron temperature for the first time on TCV.



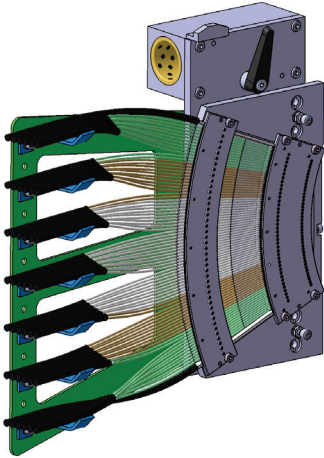
**Fig. 2.1.6** Ion and electron temperature profiles in the ELMy H-mode discharge, TCV shot #53362 where profiles in both L and H mode confinement regimes are available.

### 2.1.3 TCV Diagnostics

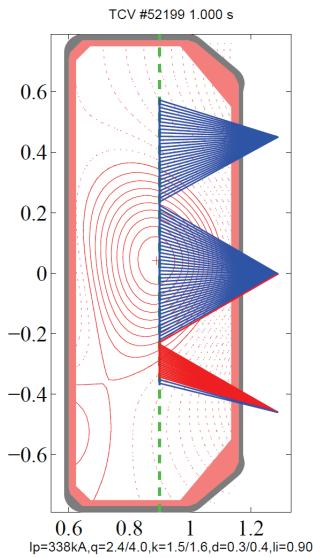
Following the 2015 restart of TCV, 2016 was a full year for diagnostics with the main effort split into progressing with the diagnostics upgrades and re-integrating the legacy diagnostic array into the upgraded TCV control system. A short résumé of noteworthy changes is reported below.

#### Thomson Scattering

This diagnostic is undergoing a major overhaul with the addition of many new spectrometers, themselves of a new design, and a new fibre optic collection array. The main goals remain to improve spatial resolution, extend reliable measurements to lower densities and/or lower temperatures and to prepare the system for Real-Time (RT) operations. In addition to the existing array of 49 spectrometers, 40 new 5-channel spectrometers, allowing measurements from 10eV to 20keV, were manufactured, tested and calibrated in 2016. A complete fibre optic front-end support was designed (Fig. 2.1.7) that avoids obscuring part of the laser path and that will allow enhanced spatial resolution on a chosen part of the laser path, shown in red on Fig. 2.1.8.



**Fig. 2.1.7** New fibre optic front end support design



**Fig. 2.1.8** Final coverage of the TCV poloidal cross-section by Thomson Scattering observation volumes. Blue lines of sight indicate spatial resolution along the laser line of ~12mm, red lines will offer ~6mm spatial resolution



### ***TCV Pressure gauges***

Two Baratron® pressure gauges were installed in the divertor and main chamber region of TCV to provide absolutely calibrated neutral pressure measurements down to 0.001 Pa with a time resolution of ~70ms. These gauges revealed peak divertor neutral compression ratios in detached plasmas of up to 15 and are serving for TCV divertor modelling.

### ***Correlation Electron Cyclotron Emission (CECE)***

The correlation ECE (CECE) system was installed on its steerable antenna. The vertical ECE (VECE) system started producing first data using radiometers donated by the Forschungszentrum Jülich.

### ***Divertor Spectroscopy System (DSS)***

In 2016 a second spectrometer was added to the DSS system with a vertical orientation that increased the number of lines of sight of the DSS system from 32 to 64. Updates for 2017 were initiated to be able to switch the secondary spectrometer between vertical or horizontal lines of sight to halve the number of discharges needed for advanced spectroscopic investigations

### ***Doppler Backscattering (DBS)***

A sweepable V-band (50-75GHz) heterodyne Doppler backscattering diagnostic was implemented in TCV in late July 2016. Ray tracing and data analysis routines are actively under development to process data from over 100 successful shots with SNR>40dB.

### ***Charge eXchange Recombination Spectroscopy (CXRS)***

The design of edge CXRS spectrometer was upgraded to employ aspherical lenses. Three new spectrometers were constructed in 2016 using this new design, The new lenses feature 40% higher transmission than the ones used in the previous design.

The edge system was commissioned in September 2016. It exploits a periscope mounted on sector 14 on the port just below the DNBI used for active CXRS. The Line Of Sight geometry made possible by the periscope increased the spatial resolution of poloidal rotation measurements from typical  $\Delta\theta > 0.1$  to  $\Delta\theta < 0.05$ . The increased throughput, made possible by the proximity of the input optics to the intersection of the line-of-sight with the DNBI, improved the uncertainty in the velocity from 2 km/s to  $\approx 1$ km/s.

### ***Fast Ion D-Alpha spectrometer (FIDA)***

One of the 2016-design spectrometers was used for FIDA diagnostics on TCV, with poloidal viewing lines. It is equipped with a 2000 1/mm holographic grating and the Asphericon 200 mm f/2 lenses. The edge spectrometry system was also used in the survey, coupled to the LFS toroidal viewing lines. The FIDA emission was dominated by passive emission in the toroidal system, and the active FIDA signal

from the DNBI cannot be extracted. The signal from the viewing lines intersecting the NBH is, conversely, dominated by the active component. It is therefore planned to use viewing lines intersecting the NBH for FIDA diagnostics on TCV. The input optics and optical fibres still require a design solution for optimised FIDA measurements.

### ***Bolometers***

A bolometer test rig was built to test the response between blackened and uncoated bolometers. A bolometer with two uncoated and two blackened foils were installed on TCV. For a limited plasma, an increase in measured power of 13-15% was observed with the blackened bolometer. This showed the need to blacken the bolometer array on TCV especially for highly radiating scenarios such as detached divertors.

### ***SPRED***

A Greateyes® CCD detector was installed, aligned and calibrated on the SPRED spectrometer. It was tested on TCV and Extreme UltraViolet (EUV) spectra were measured using both available gratings. The spectral resolution achieved is a factor of ~2-3 better than in the previous arrangement and the present JET system. Work is still necessary on magnetic and electrical shielding for successful in-shot detector pixel binning to provide ms temporal resolution. The sensitivity of the system appears sufficient for this application.

### ***Disruption Mitigation Valve (DMV)***

The DMV has been working reliably during 2016 enabling experiments in impurity transport, seeding, disruption mitigation and runaway electrons. This year the first experiments to purposely disrupt plasmas using massive gas injection were conducted. This was only possible for low-density plasmas high in the vessel due to the location and limited throughput of the DMV. The results indicated that ITER relevant disruption mitigation studies are possible on TCV, with the available plasma surface area, but require a system with higher gas throughput in a location that enables penetration into a range of plasmas, i.e. top down or bottom up injection. Hence the design a new massive gas injection system (see below).

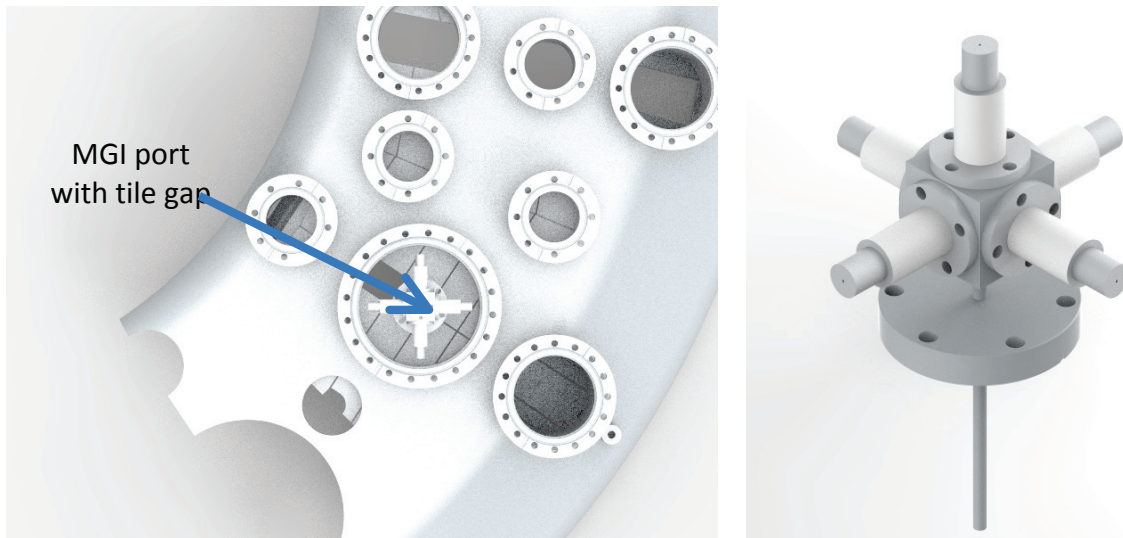
### ***Massive Gas Injection System***

A new massive gas injection system was designed (Fig. 2.1.9) and is being built. This will provide 10 times more gas flow than the current Disruption Mitigation Valve system and is positioned top-down to enable operation for a range of plasma locations and shapes. A tube is inserted into the TCV chamber to collimate the gas to possibly provide higher assimilation. Initial testing of the vacuum and electric components is scheduled for mid-March 2017. The goal is to mount the system during the opening at the end of March/early April 2017.

### ***Visible Spectrometers***

The visible Ocean survey spectroscopy system was refurbished. A few fibres that were broken and some spectrometers were decoupled from their collection optics.

The system is now in working order and analysis routines are available to monitor impurity line emission during a plasma discharge.



**Fig. 2.1.9**      *Design of the new massive gas injection system and port allocation*

### ***Pulse Height Analyser with Vertical line of sight (PHAV)***

The PHAV system was taken off the vessel after testing revealed a faulty detector. The unit was repaired and has been reinstalled. It is currently not acquiring as the data acquisition hardware is shared with the calibration system for the hard x-ray system. The aim is to have this system operational before NBH is back in use.

### ***Filtered Photodiodes***

The filtered photodiodes have been working reliably for the last year. The offsets were re-zeroed to provide the maximum dynamic range. New routines were implemented in the Diagnostician's control software that have significantly improved the reliability of the signals.

### ***Photomultiplier Tube for Hard X-Rays (PMTX)***

The PMTX power supply unit and electronics were reworked and operated reliably for 2016 providing a monitor of high-energy photons issuing from disruption mitigation and runaway electron experiments.

### ***LTCC-3D***

These non-conventional magnetic coil sensors consist of printed conductor wire coils on ceramic substrates, and are based on LTCC (low-temperature co-fired ceramic) and thick-film technology, which allow creation of monolithic multilayer coils with excellent stability. A set of three LTCC-3D sensors were installed in 2015 in TCV for the local measurements of the perturbation to the equilibrium toroidal, poloidal and radial magnetic fields. Data collected in 2016 related to MHD instabilities and turbulence with this new diagnostic system was in excellent agreement with the legacy Mirnov coil data in their common frequency range, i.e.

up to 125kHz. The higher frequency spectra measured with the LTCC-3D system indicate that, on TCV, the edge magnetic turbulence follows a Kolmogorov-like power scaling frequency to the  $-5/3$  power up to  $\sim 600$ kHz, this exponent ( $-5/3$ ) being practically independent on the operational scenario, At higher frequencies, the exponent takes values between  $-2$  and  $-5$  depending on the specific background plasma conditions.

### ***Mirnov magnetics, analysis package***

During 2016 the standard acquisition of the Mirnov coil for MHD analysis was upgraded from collection of 49 sensors at 250kHz to the full set of up to sensors for all TCV discharges with the possibility of acquiring up to 500kHz. This was instrumental in increasing the accuracy of the reconstruction of the topology of perturbations to the equilibrium magnetic field, as four different poloidal sectors (previously only one) and nine toroidal arrays (previously only two) are routinely acquired. A data analysis package was developed to perform the analysis in four separate poloidal locations, providing a much clearer understanding of possible 3D features in the TCV magnetic field.

### **2.1.4 Gyrotron physics**

Modelling activity has been focused on adapting the TWANGlinspec code for studying parasitic oscillation in smooth-wall gyrotron beam-ducts, including the possibility of a smooth-wall dielectric loading with losses on the beam-duct inner surface.

The system spatial inhomogeneity in the beam-duct region, together with the large number of potential unstable modes that have to be considered, have motivated the application of a Hybrid Finite Element (HFE) numerical scheme instead of the finite difference scheme used so far, as well as the implementation of MPI parallelization.

Dielectric permittivity properties measurements at mm-wave frequencies of a large variety of materials potentially usable as dielectric loading in gyrotron beam ducts have been intensively pursued.

In collaboration with the Laboratory of Nanostructured Materials (LPMN) of EPFL, the TWANG-series codes have been used to predict a new gyrotron operating scheme, temperature-jump Dynamic Nuclear Polarization (DNP), which has been successfully implemented using a gyrotron for DNP-Nuclear Magnetic Resonance experiments.

## **2.2 Theory**

The main goal of the theory group at SPC is to make progress in the understanding of plasma dynamics in magnetic confinement devices for fusion, in order to provide an interpretation of the experimental results from current experiments and offer suggestions to improve current and future devices. The theory group has very close ties with the TCV group, with a vigorous activity of modelling and interpretation of experimental results.

To get insight into the plasma dynamics, state-of-the-art scientific computing codes are necessary, based on a first-principles approach. The simulations carried out by the group are performed on some of the most powerful computers worldwide and tens of millions of CPU-hours have been allocated to projects led by SPC theory group members; we mention, among the HPC platforms used by the group in 2016, the Helios computer at IFERC-CSC, the Marconi-Fusion computer at CINECA, and the Piz Daint computer at CSCS (currently the most performing computer in Europe).

Computational expertise of the SPC theory group has been regularly solicited and was used to the benefit of all other research lines of SPC and of other laboratories at the EPFL and elsewhere. For example, SPC participated to the EuroFusion High Level Support Team (HLST) activities, in the framework of which a hybrid-parallelized multigrid solver was developed with MPI+OpenMP and MPI+OpenACC.

In the frame of the PASC (Platform for Advanced Scientific Computing) project of the CSCS, we continued the development of a Particle-In-Cell (PIC) code, which now includes finite element representation up to 4<sup>th</sup> order, discrete Fourier techniques, and finite Larmor radius effects, for hybrid (CPU+GPU) and many-core (MIC) architectures. The use of GPUs speeds up the code by factors of up to four as compared to using CPU alone, and parallel scalability remains good up to thousands of nodes of Piz Daint. In addition, a novel “Particle-In-Fourier” representation was developed and was shown to be significantly faster than the standard Particle-in-Cell (PIC) approach, in some cases, especially on GPUs.

In the frame of the collaboration with Lawrence Livermore National Laboratory, CA, USA, the 2+2-dimensional Vlasov code LOKI was further developed through the implementation of an improved collision model based on linearized Landau collision operators for both intra- and inter-species collisions. Symmetry and conservation properties of the collision operators up to numerical round-off could be achieved. Simulation results with this new scheme showed significant deviations in high Z plasma from the standard fluid-like collisional damping estimates based on the Braginskii equations..

In order to increase the reliability of numerical simulations, the SPC is involved in the development of rigorous verification and validation methodologies. In 2016 a methodology to perform a rigorous verification of PIC simulations was developed, both for assessing the correct implementation of the model equations, and evaluating the numerical uncertainty affecting the simulation results. The verification methodology we introduced is a generalization of the order-of-accuracy tests carried out by using the method of manufactured solutions that was introduced by the computational fluid dynamics community. The generalization of the methodology for PIC codes required to take into account the fact that the PIC approach is intrinsically affected by statistical noise and to provide a suitable measure of the distance between continuous, analytical distribution functions and finite samples of computational particles. The SPC also led a European Validation effort targeted to simulate the blob dynamics in the TORPEX experiment.

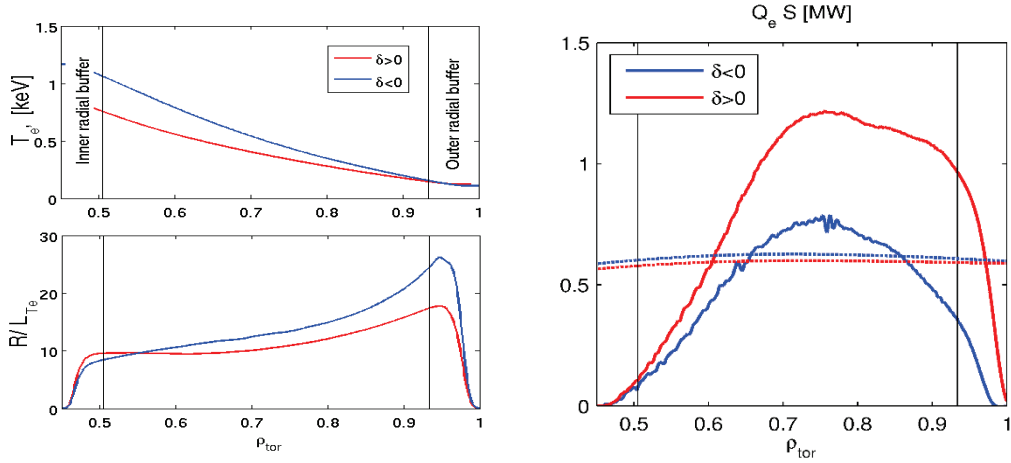
The physics investigations carried out by the theory group are focused on the following main areas of research:

- First principle based simulations of core plasma turbulence;
- MHD analysis of tokamak instabilities, 3D magnetic confinement configurations, and interaction with fast particles;
- Investigations of the plasma dynamics at the edge of fusion devices;
- Modelling activities in support of experimental activities.



### 2.2.1 First principles based simulations of core plasma turbulence

A new series of global gyrokinetic GENE simulations were carried out for studying the improved electron heat confinement observed in TCV when passing from a positive to a negative triangularity at the Last Closed Flux Surface (LCFS). A TCV discharge involving a scan of the LCFS triangularity *at* constant heating power, was considered. The runs were carried out with fully gyrokinetic deuterium ions and electrons, including electromagnetic fluctuations, as well as inter- and intra-species collisions. The computational domain covers the outer half of the TCV minor radius ( $0.45 < \rho_{\text{tor}} < 1.0$ ). This set of global simulations clearly reproduces the improved electron confinement for negative triangularity discharges over a large fraction of the plasma minor radius. As shown in Figure 2.2.1.a and 2.2.1.b, the improved electron heat confinement for negative triangularity ( $\delta_{\text{LCFS}} = -0.32$ ) is reflected in this case by the higher electron temperature values and associated gradients compared to the positive triangularity profiles ( $\delta_{\text{LCFS}} = 0.32$ ).

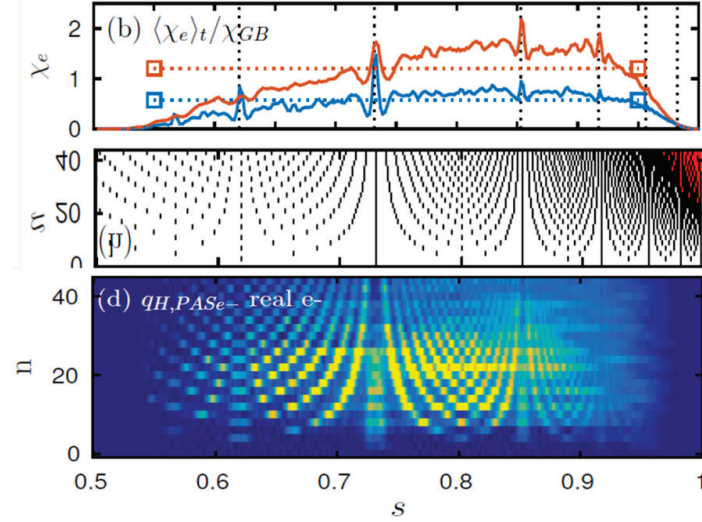


**Fig. 2.2.1** (a) Experimental electron temperature profiles and (b) corresponding gradients for TCV plasmas with triangularity  $\delta_{\text{LCFS}} = +0.32$  (in red) and  $\delta_{\text{LCFS}} = -0.32$  (in blue). (c) Electron heat power in MW crossing a given flux surface. Dashed lines indicate the experimental heating power. Vertical lines appearing in all plots correspond to the limits of radially localized buffers used for damping fluctuations at the edges of the simulation domain.

The simulated electron heat power crossing a given flux surface is shown in Fig. 2.2.1.c (for reference, the experimental heating power is indicated by dashed lines). A good agreement in the electron channel is obtained for negative triangularity, while the simulation relative to the positive triangularity still shows an overestimation of the heat flux at all radii by approximately a factor of two. Based on local simulations, this discrepancy can be at least partly explained by having neglected the effect of carbon impurities.

Turbulent transport in electron-heated TCV discharges was computed with global gyrokinetic simulations using the ORB5 code in its recently developed solver version valid for all wavelengths. The non-adiabatic passing electron response results in a remarkable radial and spectral structure of electron heat and particle

transport. In particular, because of the passing electron response, the mode rational surfaces (MRSs), corresponding to every toroidal mode number, behave as “good heat conductors” (Fig. 2.2.2, bottom and middle). The radial modulation of transport by MRSs (Fig. 2.2.2, top) results in a corrugation of the temperature profile, whereas the turbulent heat flux is radially smooth and it is a function of the radial density of MRSs.



**Fig. 2.2.2** *Electron effective heat diffusivity (top). Positions of Mode Rational Surfaces (MRSs, middle). Contributions to the passing electron heat flux vs radius ( $s$ ) and toroidal mode number ( $n$ ) (bottom).*

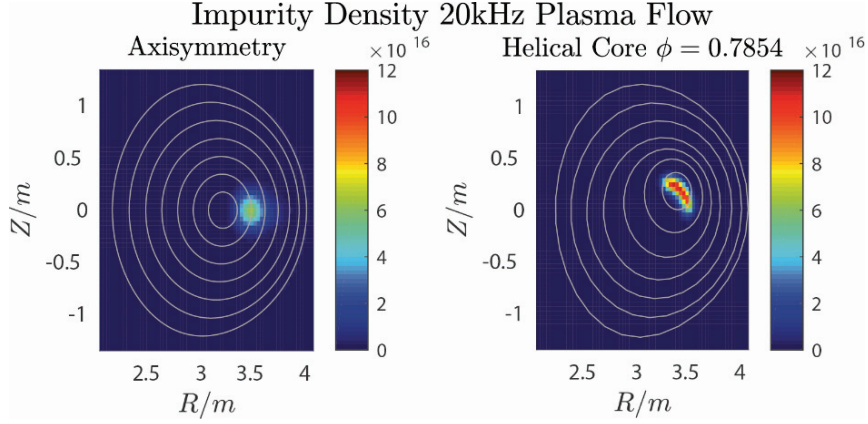
### 2.2.3 MHD analysis of tokamak instabilities, 3D magnetic confinement configurations, and interaction with fast particles

The generation of fast ions in the Wendelstein 7-X (W7-X) stellarator with ICRF waves was studied with the SCENIC package. Additionally, the VENUS-LEVIS NBI beam module was updated to handle 3D configurations. Thus realistic WVII-X stellarator NBI beam geometry is now conveniently modelled. It was found that significant particle losses and high plasma density hinder the formation of a large fast ion tail. While the classical minority heating scheme does not produce a suitable amount of fast ions for experimental confinement studies, the three-ion species scheme which allows absorption of RF power at lower minority concentrations produces a more significant fast ion tail.

The VENUS-LEVIS guiding centre code was improved to include higher-order Larmor radius corrections for the modelling of fast particle distributions at very high accuracy. The SCENIC ICRH package and VENUS-LEVIS NBI package were extensively used for JET and MAST modeling. For the case of NBI in a MAST-like equilibrium, due to inherent fast ion anisotropy, the high-order Larmor radius corrections were found to lead to significant differences in the predicted fast ion current, as well as the fast ion losses due to the interaction with resonant magnetic perturbations (RMPs).

For the application of nonlinear hybrid kinetic-MHD simulations, an innovative collision algorithm for self-collisions has been formulated. The algorithm is based on Langevin kicks on an effective Maxwellian distribution and conserves energy and momentum by construction, even when the distribution is far from Maxwellian. The

approach is adapted to the parallel environment of large hybrid fluid/kinetic simulation codes, with applications that include the fast infernal mode triggering of neoclassical tearing modes in hybrid plasmas, and nonlinear external kink modes in plasmas with strong bootstrap current.



**Fig. 2.2.3** *JET tungsten impurity density in axisymmetric rotating and kink rotating hybrid plasma.*

In preparation for future DT operation in JET, we led a hybrid scenario development campaign, attaining record neutron yields in a DD plasma at JET with the new all-metal ITER-like wall. The experiment showed that a critical issue for JET, and most likely ITER, is core tungsten accumulation during plasma operation, and the consequent effects on plasma performance and potential radiative collapse. Notably, JET plasmas are now intolerant to low- $n$  neoclassical tearing modes. In addition, impurity accumulation is exacerbated by ideal non-resonant internal kink modes that easily thrive in the extended low shear core region of hybrid plasmas. In order to model such experiments we have extended the VENUS-LEVIS code to evolve the distribution of tungsten impurities in the presence of saturated internal kink modes and strong toroidal rotation. A neoclassical collision operator has been modified to account for the parallel flow of the background ions, and in agreement with experiment, it is found that the heavy impurities quickly and strongly peak on the magnetic axis for the kinked equilibria with toroidal flow. A comparison of impurity density over the poloidal planes for rotating axisymmetric and rotating kinked equilibria is shown in Fig. 2.2.3.

Using the EPED-CH simulation tool, benchmarked with original EPED results, we performed a systematic study of the effect of the upper and lower triangularity on the pedestal height. The predicted pedestal height depends essentially on the average triangularity. The main effect of negative triangularity is to close the second stability region for high- $n$  ballooning modes, leading to a factor of four reduction in the pedestal height for a negative triangularity DEMO-like plasma versus an equivalent positive triangularity case. This has the potential to limit "by design" the maximum ELM crash and its deleterious effects.

The sawtooth and NTM models, as well as the CHEASE code, were fully integrated in the European Transport Solver (ETS) and validated with several JET discharges. Calculation in support for DEMO were carried out: we found that sawtooth periods in a standard DEMO scenario will be clearly above the limit observed for NTM triggering. Optimized launchers will be studied to test if the sawtooth period can be significantly reduced.



### **2.2.3     *Investigations of the plasma dynamics at the edge of fusion devices***

Thanks to significant implementation upgrades, the GBS code can now perform three-dimensional, flux-driven, global two-fluid turbulence simulations of SOL and edge region limited tokamaks. These simulations were used to explore the shaping effects on the SOL width, showing that negative triangularity and elongation reduce the SOL pressure scale length. The narrow power decay-length, recently found in the SOL of inner-wall limited discharges in tokamaks, was studied using GBS. The formation of the steep plasma profile was found to arise due to radially sheared  $E \times B$  poloidal flows. The effects of sheared flows were quantified, obtaining theoretical estimates in agreement with nonlinear simulations.

The novel first-principles self-consistent GBS model that couples plasma and neutral atom physics is suitable for the simulation of turbulent plasma behavior in the tokamak edge region. This was used to study the effect of neutral fluctuations on the  $D_\alpha$  light emission. Since the contributions of neutral and plasma fluctuations in neutral and plasma densities and electron temperature to the  $D_\alpha$  emission is not measured easily, their interpretation relies on simulation efforts. We found that neutral density fluctuations affect the  $D_\alpha$  emission. In particular, at a radial distance from the gas puffing smaller than the neutral mean free path, neutral density fluctuations are anti-correlated with plasma density, electron temperature, and the neutral fluctuations, reducing the  $D_\alpha$  emission.

### **2.2.4     *Modelling in support of experimental activities and real time control***

Four groups (CEA-Cadarache, GYPSA/Grenoble, ITER and TU/Eindhoven) developed  $q$ -profile and  $\beta$  controllers by using co- and counter-current drive and controlling the relative and total power, as well as the plasma current. The RAPTOR code was used as plasma simulator to replace the actual tokamak. These controllers were then implemented in TCV and tested in closed-loop feedback experiments. These tests turned out to be very successful. The whole process constitutes a first demonstration worldwide of the development and testing of the controllers that will be used in ITER. In addition, a control system was developed to integrate these  $q$  and  $\beta$  controllers with the NTM control.

Trajectory optimization of tokamak ramp-down phases was successfully applied to TCV and ASDEX Upgrade discharges. Some of the TCV cases are part of the ITER recent database of termination phases. The optimization results show that it is important to reduce elongation together with the plasma current ramp-down. The simulation tools we developed are important to find the optimal ramp-down, reducing the need for experiments.

A gradient-driven ad-hoc transport model was developed and shown to predict reliably density and temperature profiles for L- and H-modes, and the L-H transition. The model was implemented in the RAPTOR code, and successfully used to simulate the time evolution of the  $T_e$  and  $q$  profiles in TCV and ASDEX Upgrade discharges. This model was applied to sawtooth control in ITER, pointing out the importance of the launcher design geometry.

## 2.3 *Basic Plasma Physics*

The activities of the Basic Plasma Physics and Applications Group continued to focus on the TORoidal Plasma EXperiment (TORPEX) device on the study of plasma turbulence in magnetized plasmas. In the TORPEX device, plasmas with densities  $n_e \sim 10^{15} - 10^{17} \text{ m}^{-3}$  and temperatures  $T_e \sim 2 - 10 \text{ eV}$  are created and sustained by microwaves at 2.45GHz in a variety of magnetic configurations of relevance for fusion devices. These include simple magnetized toroidal (SMT) configurations with a dominant toroidal magnetic field and a small vertical field component, and closed field-line configurations using a current-carrying conductor suspended in the center of the chamber [2], which allows producing limited magnetic geometries, X-points and magnetic snowflakes. Combining a full set of plasma diagnostics together with theory and numerical modeling has allowed advancing the understanding of turbulence in magnetized plasmas to a level where quantitative comparison between theory and experiments are possible.

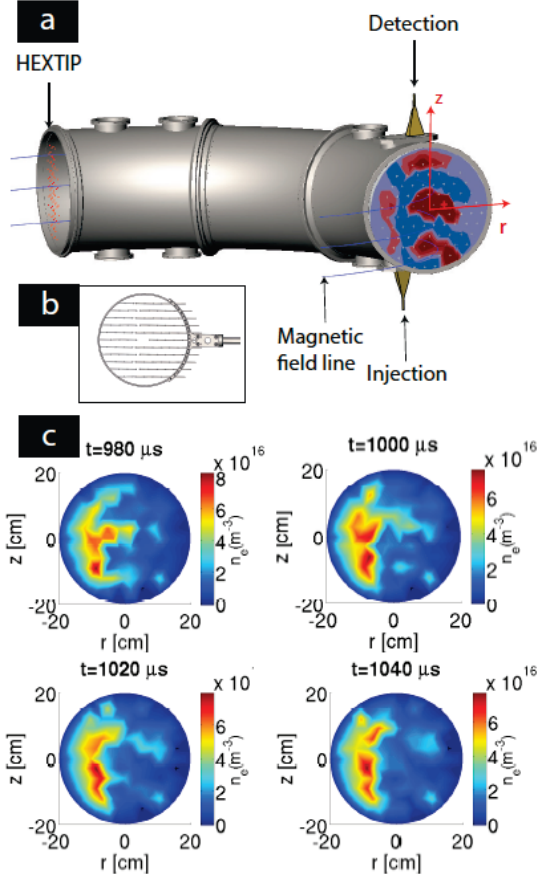
In 2016, most experiments have been conducted to investigate the interaction between intermittent plasma turbulence associated with radially propagating blobs with microwave beams and suprathermal ions, while in parallel new diagnostics developments have been undertaken to investigate the three-dimensional dynamics of blobs. The advances in these two fields are detailed below.

### 2.3.1 *Interaction of radio-frequency waves with plasma turbulence*

Understanding the propagation of electromagnetic waves in turbulent plasmas and their interactions with turbulent structures is of fundamental importance for present magnetic confinement devices, such as tokamaks and stellarators, where a significant fraction of the plasma heating is performed using mm-waves in the electron cyclotron (EC) range of frequencies. Furthermore, EC-beams are essential to surgically stabilize neoclassical tearing modes, avoiding a degradation of the core confinement or plasma disruptions. Recently, concerns over the effect of the plasma turbulence on the EC-beam propagation were addressed for the case of ITER. Turbulent structures, referred to as "blobs", present at the plasma edge and characterized by a local enhancement of the electron density, are expected to scatter the incoming mm-waves and lead to a loss of efficiency in their use. This has stimulated numerical and analytical studies suggesting that in ITER, scattering will broaden EC-beams by up to a factor two, preventing them from stabilizing tearing modes.

In 2016, we have developed a dedicated mm-system, schematically shown in Fig. 2.3.1a, to study the interaction of radiofrequency beams with intermittent blobs on TORPEX. A low-power (30mW) microwave ( $f=39\text{GHz}$ ) beam is injected in O-mode. The wave is launched using a -24dB pyramidal horn antenna. The transmitted wave is detected using an antenna similar to the one of the injection, also in O-mode. The mm-wave transmitted power is measured using a Schottky diode and digitized at 250 kHz. The mm-system is located 90 degrees away in the toroidal direction from a Langmuir probe array, dubbed HEX TIP, allowing to detect two-dimensional structures (see Fig. 2.3.1c) associated with radially propagating blobs interacting with the micro-wave beam. The experiments are conducted in the SMT configuration and allow isolating the effect of a blob on the transmitted power of the beam using a conditional sampling technique that averages the effect of several thousands individual blobs. These preliminary results represent an

important step in the understanding of the scattering of mm-waves by plasma turbulence with a characteristic size comparable to the wavelength of the wave, as in typical fusion devices.



**Fig. 2.3.1** (a) One quarter of the SMT configuration. A mm-beam is injected and detected in O-mode. (b) Hexagonal array of Langmuir probes (HEXTIP) measuring the electron density. The mm-system and the HEXTIP array are toroidally separated by 90 degrees. (c) Blob formation ( $t=980\mu s$  and  $t=1000\mu s$ ), detachment ( $t=1020\mu s$ ) and radial propagation ( $t=1040\mu s$ ).

### 2.3.2 Interaction of suprathermal ions with turbulence

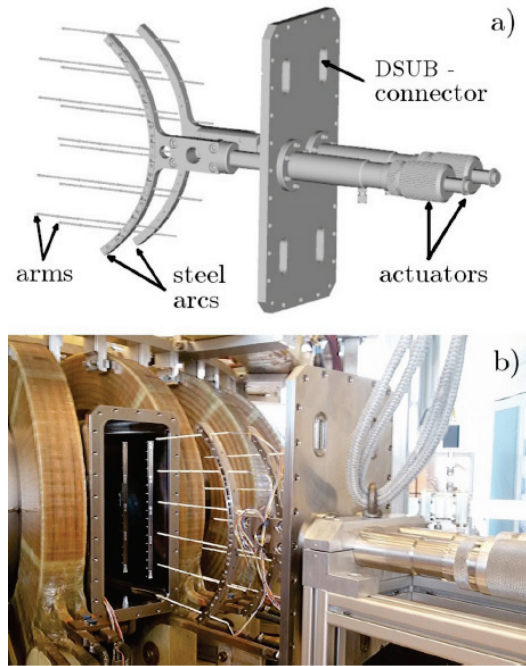
In fusion plasmas, the suprathermal ions originating e.g. from fusion reactions or neutral beam injection have long been a center of interest since their turbulent transport can impact energy deposition and plasma heating. The fundamental interactions between suprathermal ions and plasma turbulence have therefore been under longstanding investigation on the TORPEX using a beam of Li-6 ions in hydrogen plasmas of ca. 1eV in SMT configurations. A set of two back-to-back Gridded Energy Analysers (GEAs) capture the time-resolved fast ion current, as well as time-averaged beam profiles. In combination with predictions from the GBS code, three consecutive phases of non-diffusive transport were established. After an initial ballistic phase lasting approximately for a gyro-period, fast ions of ca. 70eV exhibit sub-diffusion and those of ca. 30eV rather super-diffusion in the ‘interaction phase’. While ions of larger Larmor-radii would gyro-average over typical turbulent structures – especially intermittent plasma filaments (‘blobs’) – those of smaller Larmor-radii would experience a more consistent drift due to the turbulent electric fields in blobs. The time-resolved super-diffusive fast-ion current reflected the intermittency of the blobs, while the sub-diffusive equivalent did not. Once the ion-beam is sufficiently broad to experience a significant radial variation of plasma-parameters, it enters the ‘asymmetric phase’ of transport, in which all ion-energies show sub-diffusion.

These studies have been resumed in 2016. Multiple improvements to experimental equipment have been brought underway, such as a more finely calibrated resolution of 1mm for ion-beam profiles, as well as the acquisition of a time-resolved estimate of the total injected ion-current and a new amplification-circuit for the GEAs contributing to noise-reduction. These are to facilitate the investigation of intermittency in time-resolved fast-ion-currents in all transport phases, which have commenced with trials in the asymmetric phase. Due to the wide spread of the ion-beam and hence weakened signals, findings are preliminary so far, but indicate promising trends that are currently being explored. Various fractional diffusion models for non-diffusive transport have been reviewed – especially the established types of Continuous Time Random Walks and those based on the Generalised Langevin Equation. Their different ways of implementing non-markovian features are soon being assessed with regards to experimental data in more detail. Truncation effects on the underlying heavy-tailed step-size distributions will be investigated as well.

### ***2.3.3 Diagnostics development to investigate three-dimensional blob physics***

Past studies of blob physics on TORPEX have significantly contributed to the understanding of perpendicular dynamics (across magnetic field lines) of plasma blobs of importance for fusion grade devices. These advances have been possible thanks to the use of multiple LP arrays, which have also enabled experimental studies of parallel dynamics (along the magnetic field), leading to important results in, among others, wavenumbers of fluctuations. There are still, however, many open questions on the experimental three-dimensional (3D) dynamics of blobs. Furthermore, 3D effects are suspected to be at the origin of many differences currently observed between experimental data and models of blobs. Indeed, many theories neglected variations along the magnetic field lines, an assumption that is well motivated in many cases but may not be appropriate in general.

In 2016, we have designed and installed a new Langmuir-probe (LP) array diagnostic to determine basic 3D features of plasmas in TORPEX. The diagnostic, shown in Fig. 2.3.2, consists of two identical LP arrays, placed on opposite sides of the apparatus, which provide comprehensive coverage of the poloidal cross section at the two different toroidal locations. The LP arrays include a linear-motion mechanism that can displace radially the probes located on the low field side for experiments that require fine-tuning of the probe locations, and for operational compatibility with the in-vessel toroidal conductor. To date, we have demonstrated that cross correlation studies of signals from the arrays provide a basic way to extract 3D information from the plasma. Moreover, the remarkable signal-to-noise performance of the front-end electronics allows us to follow a different approach in which we combine information from all probes in both arrays to reconstruct elementary 3D plasma structures at each acquisition time step. Then, through data analysis, we track the structures as they evolve in time. Further dedicated studies will follow to fully explore plasma dynamics with closed field lines, a subject that is of direct relevance to the understanding of tokamak physics.



**Fig. 2.3.2** *Low Field Side (LFS) probe assembly. (a) Design schematics showing the support arcs for the ceramic arms and the linear motion mechanism. (b) Complete LFS assembly during installation.*

#### **2.3.4 Plasma Applications**

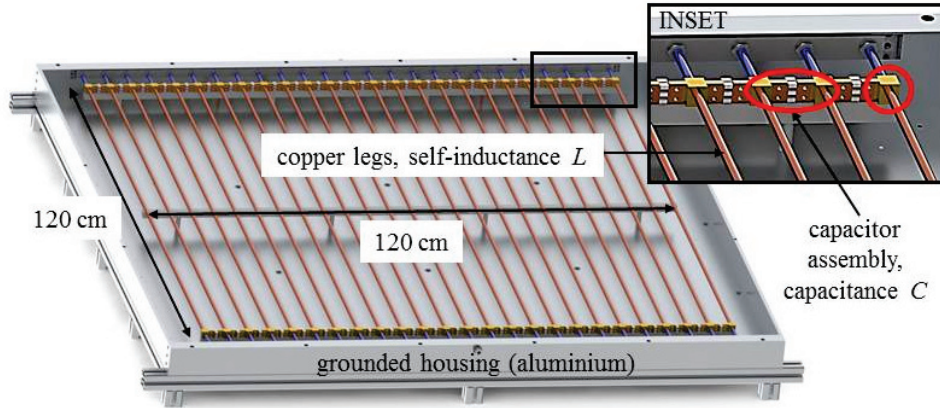
The second aspect of the activities of the Basic Plasma Physics and Applications group is to develop new applications of low temperature plasmas and advance their basic physics understanding. In the period covered by this Report, consolidated projects with previous industrial partners and European projects continued, including the development of a new theory to model large area resonant RF network antennas, previously developed in collaboration with TetraPak, a H2020 project to develop passive mitigation methods of gas breakdown for satellite slip rings, and a EuroFusion project for plasma source development for negative ion neutral beams.

#### **2.3.5 Flat inductive plasma for large area plasma processing and theory**

Plasma processing over large areas ( $> 1 \text{ m}^2$ ) is required for the industrial production of solar cells, flat panel displays, packaging, surface treatment, large area electronics, etc. Magnetic induction by RF oscillating currents in parallel legs is often used to drive the plasma in large inductive sources. In previous years, in the framework of a collaboration between Tetra Pak, Helyssen Sàrl, and the Swiss Plasma Center, we developed a large area resonant antenna for a full-sized industrial coating applications. The novel antenna is a multiple  $LC$  resonant network as shown in Fig. 2.3.3 and was successfully tested by Tetra Pak. In the period covered by this report, we developed a new theory to model large area flat inductive sources. An electromagnetic model describes the antenna-plasma coupled system as a multi-conductor transmission line. Inspired by the “complex image”



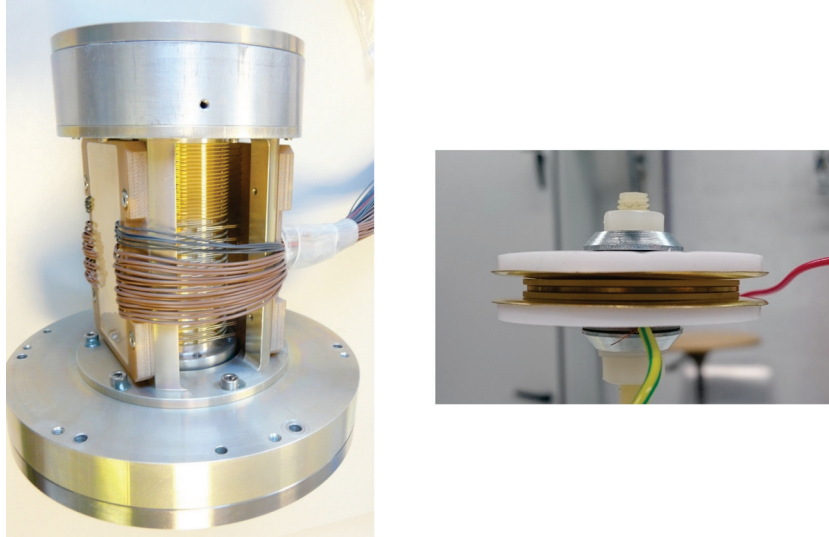
model for power transmission lines, this theory is used for the first time to calculate the induced image currents in the plasma.



**Fig. 2.3.3** Schematic of the  $1.2 \times 1.2 \text{ m}^2$  planar antenna. Capacitors join the ends of copper leg inductors to form a LC resonant network.

### 2.3.6 Gas breakdown investigation and mitigation in complex geometries

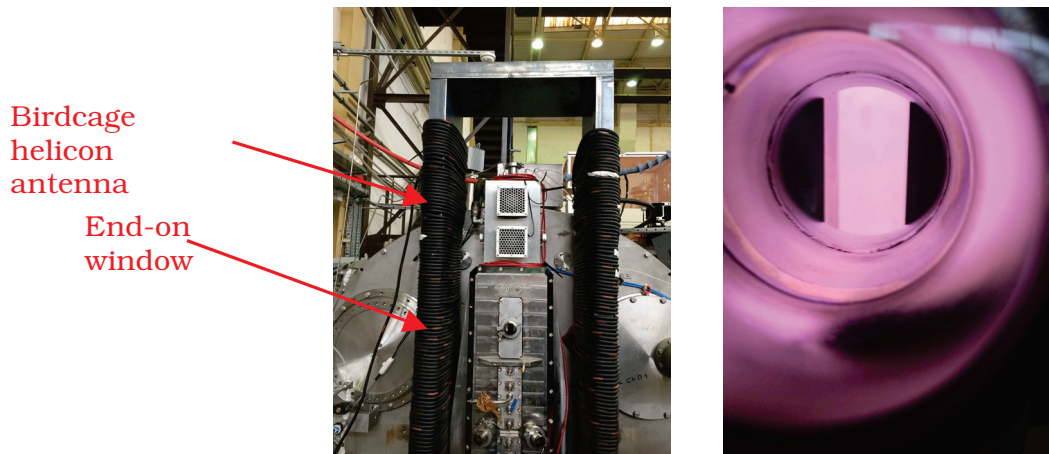
The gas breakdown inhibition in electrical circuits of satellites is a technological challenge. The satellite components that are mostly prone to electrical breakdown are the solar panels, constituting the power source, and the slip ring assembly (SRA), which is part of the power transmission circuit. From current bus voltages in the range 28-100V, evaluation of interest in using higher voltages in the range 300-600V is under way, with the corresponding much higher risk of electrical breakdown. These voltages are required to power new generations of ion and Hall Effect thrusters and to increase the efficiency of the satellite. In the framework of a H2020 program and in collaboration with Ruag Space in Nyon, we are investigating gas breakdown on the standard cylindrical configuration of a SRA, shown in Fig. 2.3.4(left), which ensures the electrical power transmission between the rotating solar panels and the rest of the satellite via gold-plated brushes slipping on gold-plated rings. The aim of this project is to optimize the slip ring design to inhibit breakdown, improving the state-of-the-art of electrical power supply in satellite. A simplified SRA is investigated, both experimentally in a dedicated laboratory setup, in Fig. 2.3.4(right), and with numerical simulations, by varying several geometrical parameters and component materials. An innovative technical solution is introduced to inhibit the gas discharges at low-pressures in SRA: the diameter of the grounded conducting discs is extended, strongly increasing the measured breakdown voltages, thereby increasing the safe operating pressure range of the satellite slip ring by two orders of magnitude.



**Fig. 2.3.4**      *Left: Cylindrical slip ring for a satellite. Right: slip ring assemblyS mockup for basic investigations in the dedicated laboratory setup at SPC.*

### **2.3.7      *Helicon plasma source for negative ions production***

In the framework of a EUROfusion project and in collaboration with CEA-Cadarache, we developed a 10 kW birdcage antenna plasma source at SPC to investigate the main technology and physics issues of helicon-generated plasmas for applications as negative ion source for fusion. In 2016, the construction of the helicon plasma generator based on a birdcage resonant antenna was concluded and preliminary tests of its performance were done on the Resonant Antenna Ion Device (RAID) at SPC. These include tests with Hydrogen (H) and Deuterium (D) gas at different pressures, magnetic field and radiofrequency power levels, spectroscopic measurements of the H/D dissociation rate and Langmuir probe measurements of electron density and temperature profiles. Stable operation in both H and D were obtained for the working nominal conditions required in the Cybele negative ion source, namely 0.3 Pa of pressure and approximately 120 G of magnetic field. We performed detailed measurements of the absolute emissivity profiles for the first three Balmer lines and the molecular diagonal Fulcher- lines in H and D plasmas. The absolute line emissivities were interpreted using the collisional-radiative code YACORA. The results obtained are promising for application of the antenna as a negative ion source. Finally, the commissioning of the birdcage helicon antenna was successfully completed on the Cybele device. A picture of the birdcage antenna installed on Cybele together with the first Argon plasma are shown in Fig. 2.3.5.



**Fig. 2.3.5** Left: Antenna installed on Cybele. Right: first helicon plasma in Argon in Cybele seen from an end-on Cybele window.

## 2.4 Superconductivity

### 2.4.1 Superconducting Magnets for DEMO

For the 83kA/13.5T, React&Wind Nb<sub>3</sub>Sn conductor (RW1), an artefact at the termination prevented in 2015 achieving operating current > 80kA. In 2016, the conductor has been dismantled and the layer of copper wires has been replaced by solid copper profiles, improving the lateral support against Lorenz forces. The T<sub>cs</sub> performance improved by about 1 K, fully validating the design approach.

The 63kA/12.5T prototype conductor for the baseline design 2015 (RW2) was procured in 2016. The assembly is about completion at the end of 2016. The test is planned early 2017. The full set of supporting analysis for the TF winding pack made of RW2 is completed.

The issue of performance degradation upon cyclic load in the 60kA/12.5T/5K High Temperature Superconductor (HTS) prototype conductor was investigated in 2016 on a number of strands mechanically loaded and tested at liquid nitrogen up to 5000 cycles. Two new strand layouts are designed for a new HTS prototype conductor, representative for the CS high grade, to be assembled in 2017.

The design studies for an optimized DEMO Central Solenoid continued in 2016. The peak field is now 18T at the HTS grade. The effects of the vertical loads are now accounted for.

Beside the test of the SPC conductors, the ENEA prototype conductor for TF DEMO (Wind&React, WR1) was tested in the EDIPO test facility in April 2016 (performance test) and in SULTAN in July 2016 (hydraulic test).

### 2.4.2 Development of high field insert coil made of HTS tapes

The electric scheme of the quench protection was finalised and the magnet was prepared for the installation of the insert. Only at the end of 2016 the suppliers



were able to complete the manufacture of the 600m of tape needed for the fabrication of the final insert; tape samples were tested in liquid helium.

In the meanwhile a test coil (similar inner and outer diameters but shorter than the insert) was wound and impregnated; the test was carried out at 77K.

#### **2.4.3 *EDIPO test facility***

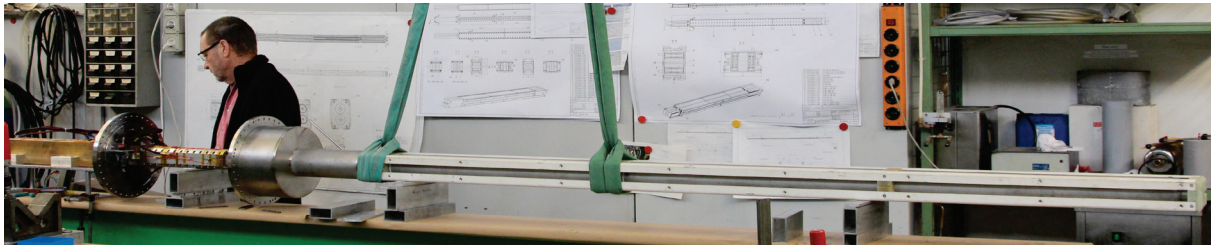
In the first half of 2016, the EDIPO test facility was used for the test of the DEMO TF conductor prototypes, RW1 and WR1. On May 31<sup>st</sup>, a high field quench led to the destruction of the coil assembly, due to a manipulation of the quench protection software. The coil assembly was removed from the cryostat and plans are considered to restore the test facility in the scope of a broad international collaboration.

#### **2.4.4 *Non-destructive methods for ITER joints***

The trials with mock-up terminations prepared with intentional defects are completed in spring 2016 and a full report is handed to the ITER Organization. The ability of the proposed method to clearly detect operation relevant defects in the connections at room temperature is rather poor. The follow up activity, with benchmark by cryogenic tests and eventual use of the equipment in-situ at the ITER TF coil manufacturers, is not pursued by ITER.

#### **2.4.5 *Test of HTS dipole inserts for CERN***

Under collaboration contract with CERN, a cryostat has been designed and manufactured to test under variable operating temperature a number of HTS prototype dipole inserts. The cryostat fits in the test well of SULTAN and is equipped with HTS current leads, to be connected to the SULTAN transformer, designed to carry up to 20kA. At the end of 2016 the cryostat was assembled, see Fig. 2.4.1. Commissioning (with a short circuit in place of the actual HTS insert) is planned early 2017.



**Fig. 2.4.1** *Final assembly phase of the cryostat for the test of the HTS insert dipoles from CERN.*

#### **2.4.6 Tests of superconductors for ITER in SULTAN**

The tests of the PF conductors were completed in January 2016. The tests of the TF conductors were completed in autumn 2016. The test of the CS conductor and joint samples continued in 2016 and beyond. The following test campaigns have been carried out in 2016 for 19 samples:

- PFRF4 – RFDA – PF1 sample from Russian series production – 1 week
- CCCNjoint – CNDA – Qualification of industrial CC joint sample – 1 week
- TFJEU4 – F4E – Qualification of industrial TF joint sample – 1 week
- CSJA9 – JADA – CS sample from series production – 5 weeks
- CFETR– CNDA – Qualification of CS conductor for CFETR – 5 week
- PFJEU2 – F4E – Pre-qualification joint sample for PF5 – 2 week
- TFinsert – JADA – TF sample from series production – 5 weeks
- TFJEU5 – F4E – Qualification of industrial TF joint sample – 1 week
- TFUS7 – USDA - TF process qualification sample from US – 3 weeks
- TFJEU6 – F4E – Qualification of industrial TF joint sample – 1 week
- TFJEU7 – F4E – Qualification of industrial TF joint sample – 1 week
- TFUS8 – USDA - TF sample from series production – 2 weeks
- TFJEU6 re-test– F4E – Qualification of industrial TF joint sample – 1 week
- PFJEU1 – F4E – Pre-qualification joint sample for PF6 – 1 week
- CSJA10 – JADA – CS sample from series production – 5+1 weeks
- PFJEU3 – F4E – Qualification joint sample for PF5 – 1 week
- TFCN6 – CNDA – TF sample from Chinese series production – 2 weeks
- TFJEU3 – F4E – Qualification of industrial TF joint sample – 1 week
- PFJEU5 – F4E – Qualification joint sample for PF6 – 1 week

### **2.5 International and National activities**

#### **2.5.1 Gyrotron development for ITER**

The European Gyrotron Consortium (EGYC) activities in 2016 were focused on the exploitation of the first continuous wave (CW) 170GHz/1MW gyrotron prototype manufactured by Thales Electron Devices (TED), in the frame of the F4E procurement contract OPE-447 at KIT.

During the year, the tube was extensively characterized, first with short pulses in order to reproduce results obtained with the short pulse (SP) version of the tube, and then with long pulses (<180s, limited by the power supplies).

The short pulse campaign revealed a slightly different behavior of the CW tube compared to the SP version. It was possible to reach the MW level in single mode oscillation, but in a reduced range of parameters. The reasons for this discrepancy were carefully diagnosed, and it is commonly agreed that an alignment problem in the electron gun or in the RF structure is the most probable cause.

Despite this difference, the CW tube produced excellent results, with a best achieved performance of 800kW/180s.

The tube will be dispatched to Lausanne to prolong the experimental period with the goals of extending the pulse length to 1 hour and performing modulation and reliability tests.

In parallel with these activities, deep modifications of the SPC European Gyrotron Test Stand were undertaken, with the following guide lines:

- Prepare the stand to host the CW tube (modification of the cooling circuits, of the gyrotron tower, preparation of new cooling and/or calorimetry devices).
- The superconducting magnet (SCM) that will host the European CW prototype was delivered end of 2016 and the Site acceptance test was passed in January 2017.
- Modification of the test stand to host the FALCON test stand (see corresponding paragraph)
- Update of the Control and protection system, as well as data acquisition, to make it ITER compatible. These activities are carried out in the frame of an F4E procurement contract (OPE-733).

### ***2.5.2 EC Upper Launcher (UL) development for ITER***

The European Launcher Consortium (ECHUL) activities continued in 2016 under the new grant GRT-615 (essentially a large amendment of the previous grant GRT-161). The waveguide components between the port plug and the diamond window are part of the first confinement system (FCS) of the ITER tokamak and are therefore subjected to the most stringent quality, safety, and vacuum requirements. Work in 2016 has concentrated on the 3<sup>rd</sup> update of the Configuration Management Model for the ITER Enovia database, the design of the isolation valve, the supports of the FCS and the cooling of components. The models of all FCS components have been further improved to comply with the ITER CAD standards, in line with the Project Change Requests (PCRs) received to date. In addition, work has continued to update and check the Sub-System Requirement Document that gathers all the relevant constraints on the system. The millimeter wave loads on the components have been updated based on published results from waveguide prototype tests carried out by other ITER Domestic Agencies (DAs). These loads provide input data for the design of the Component Cooling Water System (CCWS-1) and design of the mm-wave components, which has advanced far enough to permit a change in priority to in-vessel components.

Work within a service contract with F4E to provide Support to Prototype Procurement & Qualification of EC Isolation Valves (OPE-667) has continued. The isolation valve is a critical component between the diamond window and the port plug. OPE-667 is the first contract for SPC of a Protection Important Class 1 and quality class 1. Extensive support to F4E has been provided to write and consolidate the Component Load Specifications (CLS), the Component Failure Mode and Effects Analysis (FMEA), the evaluation of Reliability Availability Maintainability and Inspectability (RAMI), elaboration of the Configuration Management Model (CMM) and the Component Requirement Document (CRD); as well as defining The Qualification Programme Document (QPD) for the Isolation Valve.

Due to production constraints, high power testing of prototypes will require a test facility in the EU. An European high power gyrotron testing facility (GT170) was

installed at SPC for long-pulse R&D and qualification testing of the EU ITER gyrotron (see 2.5.1). A service contract for the Design of the ECT-FALCON Facility OPE-733 was executed. This test facility will be provided with a second 1MW, 170GHz, 1000s gyrotron supplied by F4E and acting only as a power source for UL component testing. Upon completion of the design contract, a successful bid for a 7 year Framework Contract OFC-671 was made. The first Task Order of the OFC was launched that the end of the year to implement the design of the facility, to participate in the Factory Acceptance Test of the gyrotron and to perform the Site Acceptance Test in the facility in collaboration with F4E and the gyrotron manufacturer. Additionally, SPC will install the Control System provided by F4E that aims at demonstrating an intermediate step between present day systems and the fully ITER compatible system. Finally, SPC will provide assistance to F4E and IO for the Site Acceptance Tests of the RF Loads, gyrotron superconducting magnet and Gyrotron Conditioning Components.

### ***2.5.3 ITERIS: Design and first applications of the ITER Integrated Modelling & Analysis Suite (IMAS)***

The ITERIS contract has been continued as Task Order Nr 4 in 2016, however on a much reduced level. This will be the case for 2017 as well. Continued support for CHEASE, the suite of interpolation and extrapolation routines has been provided. A tool for transforming equilibria according to the COCOS index has been implemented as well.

### ***2.5.4 Work package Heating and Current Drive (WPHCD) in the frame of EUROfusion***

#### ***Modelling and experiments of spurious instabilities in smooth-wall dielectric-loaded gyrotron beam-ducts***

For parasitic oscillations studies in smooth-wall beam-ducts (BD), following a detailed numerical analysis of finite-difference (FD) and hybrid-finite elements (HFE) schemes, a significant effort has been carried out for parallelizing the TWANGlinspec (HFE) spectral code using MPI (Message Passing Interface). This allows for the simulation of a large number of potential transverse modes in a reasonable time to solution. In addition, a reliable numerical scheme for calculating the fully self-consistent minimum starting current has been successfully implemented, with the possibility of including system parameter scans. The adaptation of the TWANGlinspec code for dielectric loaded smooth BD is ongoing.

Dielectric permittivity property measurements of different BD-relevant materials including the temperature dependence have been performed. Measurements of dielectric permittivity for relevant dielectrics have shown a large spread in dielectric properties for BeOSiC samples from the same company. A strong temperature dependence of the dielectric properties has been measured with very different dependencies between BeOSiC and SiC (Cerasic-B).

### **2.5.5     *Work package Plant level System Engineering, Design Integration and Physics Integration (WPPMI) in the frame of EUROfusion***

Alpha particle losses and the associated heat fluxes on the surface marking the plasma boundary have been calculated in 3D MHD equilibria that are generated in the DEMO coil configuration using the particle orbit code VENUS-LEVIS. The VENUS-LEVIS results were verified in two ways: first, the conventional guiding-centre model is compared to a recently developed model including corrections that are higher-order in Larmor radius than usually implemented. Second, a comparison between the results obtained from the VENUS-LEVIS and ASCOT codes is made, using for both codes the conventional guiding-centre following method for this exercise. In comparison to previous studies, the equilibrium used for the present benchmark is positioned slightly closer to vessel wall on the low-field side, which is found to noticeably increase the ripple and hence the ripple induced losses.

It is found that conventional guiding-centre following is sufficient for calculating particle orbits in DEMO. The difference between higher-order and conventional guiding-centre following is within other modelling uncertainties. The results obtained using VENUS-LEVIS and ASCOT, while in qualitative agreement, exhibit quantitative differences, in particular in the collision-dominated regime. Such differences lead to a lower level of predicted losses from the ASCOT simulations (total heat flux 1315kW) as compared to VENUS-LEVIS simulations (total heat flux 1571kW).

Considering the general strategy for this area, the first phase of the study of fast ion orbit losses due to field imperfections can be considered concluded. The next period will be dedicated to refine the transport scenario analyses, so that the kinetic plasma profiles will be better estimated. This will enable the creation of a credible set of reference scenarios for the calculations of the wave-particle interaction contributions to the fast ion transport.

### **2.5.6     *Contribution to the scientific exploitation of JET***

SPC collaborators co-led the development of hybrid scenarios in JET. The objective was to establish high performance plasmas in order to prepare the scenarios that will be used during the deuterium-tritium (DT) campaign in two years time. A particular feature of hybrid scenarios is that sawteeth are avoided by maintaining the safety factor slightly above unity during the entire high performance phase. This requires that auxiliary heating is applied early, and that the plasma is sufficiently hot so that the consequentially slow resistive diffusion locks the safety factor for the whole pulse. In addition, plasma beta should be high enough for a significant bootstrap current to develop, which helps to develop the desired q-profile. Such high performance plasmas are susceptible to beta driven neoclassical tearing modes (NTMs). These modes directly reduce the performance of the plasma, and pose a disruption risk, but in addition they cause tungsten impurities to migrate to the core of the plasma, thus further reducing performance and sometimes instigating radiative collapse. Furthermore, infrequent edge localized modes (ELMs) also cause impurities to migrate to the core. The ELMs can be regularized by increasing the gas dosing of the plasma. Real time control of the ELM period by gas dosing was in fact demonstrated, thereby also limiting the negative effect of unnecessarily high edge density. To attain high performance plasmas, the



highest possible auxiliary heating power must be applied, but in order that the beam ions reach the plasma core the plasma density cannot be allowed to become too large, so that peaked plasma pressure and beta are achieved via temperature peaking rather than by density peaking. Peaked temperature profiles and flat density profiles also prevent neoclassical and turbulent driven impurity influx. Additionally, such profiles are optimal for fusion reactivity, which in the experiments over 2016 was measured by the neutron yield from D-D reactions. All of these issues were optimized in the hybrid development experiments, together with techniques for mitigating melting of the divertor by regular sweeping of the magnetic field strike point positions. Despite all of these simultaneous requirements for good plasma performance and machine safety, a window of operation was found, and the experiments were largely successful. Reliable auxiliary heating power of up to 33MW over 5s enabled world record neutron yields in an all-metal device. ELMs were successfully controlled, core MHD avoided, and high beta maintained for around 3-5s. Scaling to future DT experiments indicates that it should be possible to obtain around 8MW of fusion power for up to 5s. The scaling takes into account that more auxiliary power will be available than in 2016, and the magnetic field and current will be larger.

In addition to coordinating these experiments, SPC collaborators deployed the SCENIC ICRH modelling package for supporting various experiments, including hybrid scenario development, 3-ion heating experiments during the hydrogen campaign and advanced scenarios developed for fast ion studies.

### ***2.5.7 Contribution to the scientific exploitation of Asdex-Upgrade***

SPC contributed to several experiments on Asdex-Upgrade in 2016 in the frame of the EUROfusion MST1 project, as co-scientific coordinators and as contributors for experimental planning and analysis.

These experiments cover various topics like increasing the edge pedestal pressure values by avoiding pressure-driven ideal MHD short wavelength instabilities (the so-called “ballooning boundary”), while others were aiming for small ELMs with good confinement and high density using the proximity to double null, i.e. configurations where a second X-point is present close to the inner magnetic separatrix. Very good preliminary results have been obtained, although further developments are necessary. These results were also inspiring similar studies subsequently performed on TCV. We also contributed to NTM control and disruption avoidance, as well as improving real-time observers. In order to achieve these goals, the RAPTOR code has been extended to solve the transport equations with time-varying equilibrium and density profiles, and a new transport model has been implemented, allowing for fast simulations of the time evolution of the profiles over full discharges, validated on several Asdex-Upgrade discharges. This model has been used to propose optimized ramp-down scenarios avoiding disruptions.

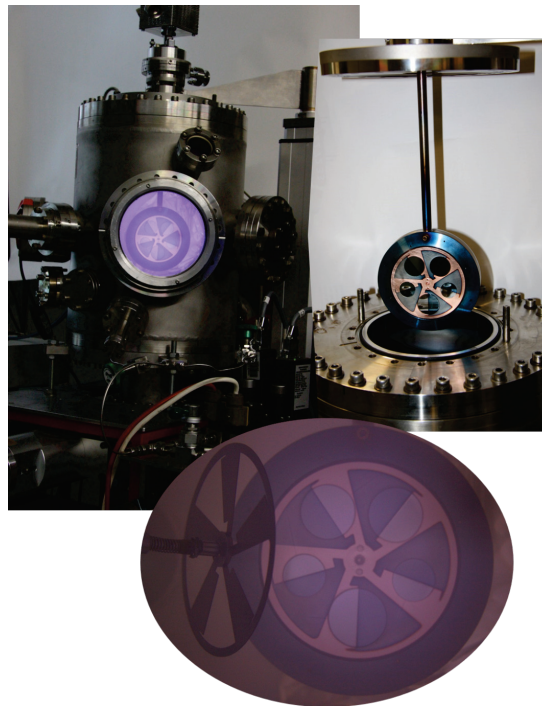
### ***2.5.8 Work package Divertor Tokamak Test Facility (WPD TT1) in the frame of EUROfusion***

The SPC-led project on the assessment of the reactor compatibility of alternative plasma exhaust solution released a first report. The report analyses constraints, costs and performance improvements of a set of alternative magnetic divertor configurations as well as divertor targets made out of liquid metals. The assessment

did not find any show-stoppers. It showed that alternative divertor configurations can in principle be implemented in a reactor size device within presently accepted engineering limits on forces on the magnetic coils. Similarly, it identified temperature windows for divertor targets made out of liquid lithium and liquid tin that may be compatible with low tritium retention and acceptable evaporation fluxes. The assessment, however, also highlighted that quantitative predictions of performance improvements are still outstanding. The work in the project has provided a basis for the development of a European strategy to close the gaps in the plasma exhaust area.

#### ***2.5.9 Plasma surface interactions in collaboration with the University of Basel***

With the aim of in-situ cleaning of first mirrors in ITER, we have developed and tested a plasma-based method in our laboratory and assessed its feasibility. Experiments to validate the technique of plasma cleaning are going on in Basel under a contract with F4E. More than 30 mirrors were manufactured including stainless steel (SS) mirrors, molybdenum (Mo) as single crystal (Sc) and as polycrystalline (Pc). On top of SS were deposited nanocrystal-line rhodium (NcRh) and Mo (NcMo) by magnetron sputtering. The specular reflectivity of all Mo and Rh mirrors were comparable to the reference one. Also on top of SS, aluminium / zirconium oxide (Al/ZrO<sub>2</sub>) coatings were deposited by magnetron sputtering. Deposition of ZrO<sub>2</sub> films was performed using either a direct current (DC) or a radio frequency (RF) excitation. The optical index of ZrO<sub>2</sub> film was optimized using different oxygen mixture. All films thicknesses were cross-checked by quartz microbalance and cross-section secondary electron microscopy (SEM).



***Fig. 2.5.1***      *New electrode with 5, including a shutter to deposit a dust film on half of the mirror to be able to carry out cleaning cycle.*

Layers of 25nm of aluminum oxide ( $\text{Al}_2\text{O}_3$ ) and aluminum tungsten film (Al/W) were deposited on top of mirrors as dust film. The plasma cleaning was carried out by applying RF excitation at either 13.56 or 60MHz using helium (He) or argon (Ar) gas. After more than 16 cleaning experiments it was decided to use Ar and 60MHz for test of multiple cycles.

Two sets of electrodes and shutters were manufactured to fix 5 or 6 mirrors simultaneously and allow depositing half of the mirror (Fig. 2.5.1). Using this new equipment, 20 cycles of cleaning on mirrors procured by University of Basel were carried out. The diffusion and roughness of the PcMo increased significantly at the end, but that was not the case for ScMo. For Al/ $\text{ZrO}_2$  mirror, after 3 cycles the film of  $\text{ZrO}_2$  was sputtered away. For both NcMo and NcRh the specular reflectivity after 10 cycles was similar as the pristine one. Due to film thickness, for 20 cycles the entire NcRh and NcMo were sputtered away.



## 3 THE EDUCATIONAL ROLE OF THE SPC

The Swiss Plasma Center plays an important role in the education of undergraduate and postgraduate students, particularly in the Faculty of Basic Sciences (FSB) of the EPFL. Advanced education and training in fusion physics and technology and plasma physics topics is carried out as part of the research activities of the Association. Section 3.1 presents the courses given to physics and engineering undergraduates while SPC contributions to Master and Doctoral studies are detailed in Sections 3.2 and 3.3. As an academic institution, the SPC supervises many PhD theses, in the frame of the Physics Doctoral School of the EPFL. Four PhDs were awarded in 2016. At the end of 2016 we had 34 PhD students supervised by SPC members, in Lausanne and at the PSI site in Villigen. Their work is summarised in Section 3.4.

### 3.1 *Bachelor courses given by SPC staff*

#### **A. Fasoli**, Professor – “*General Physics II*”

This course, given to the SV Section, completes the introduction to mechanics provided in the first semester with the basic concepts of statics, oscillations and special relativity. It also covers the whole of thermodynamics, from the introduction to heat, temperature and kinetic theory to the first and second principles, including entropy and thermal engines, ending with a treatment of transport and non-equilibrium phenomena in open systems.

#### **A. Fasoli**, Professor and **I. Furno**, Maître d'Enseignement et Recherche (MER) – “*Energy for Global Issues*”

Energy involves scientific, technological and societal issues. In this course, all of these aspects are treated in an intertwined way, from the basic concepts to the needs and resources, as well as societal and political implications. The goal is to provide the students with quantitative tools and to present a global overview of the issue, to form a sufficient background enabling them to discuss in an informed way, and possibly contribute to, various aspects of the energy problem.

#### **P. Ricci**, Associate Professor – “*General physics II*”

This course is given to the STI Section. It provides an introduction to special relativity and thermodynamics.

#### **M.Q. Tran**, Professor - “*General Physics II*”

This course, given to the Mathematics Section, covers mechanics and thermodynamics.

#### **S. Brunner**, Maître d'Enseignement et Recherche (MER) and **J.P. Graves**, Maître d'Enseignement et Recherche (MER) - Mathematical methods for physicists

This course, taught to 4th semester Bachelor Students in Physics, complements the Analysis and Linear Algebra courses in providing further mathematical background required for 3rd year physics courses, in particular electrodynamics and quantum mechanics. It covers an introduction to Hilbert spaces, 2nd order Ordinary Differential Equations (ODEs), Frobenius method, boundary value problems, Sturm-Liouville problems, Fourier Series, Fourier Transforms, special functions and various methods for solving Partial Differential Equations (PDEs).

**L. Villard**, Professeur Titulaire – *"Computational Physics I-II"*

Full year course given to students in their 2nd year in Physics. The course covers various time and space integration techniques for ordinary and partial differential equations, and is applied to various physics problems ranging from particle dynamics, hydrodynamical equilibrium, electromagnetism, waves and quantum mechanics. It includes a strong practical work aspect.

**S. Alberti**, Maître d'Enseignement et Recherche – *"Plasma Physics I"*

This course is an introduction to plasma physics aimed at giving an overall view of the essential properties of a plasma and at presenting the approaches commonly used to describe its behaviour. Single particle motion and different fluid models are studied. The relation between plasma physics and developing a thermonuclear reactor is presented and illustrated with examples.

**A. Fasoli**, Professor, **I. Furno**, Maître d'Enseignement et Recherche (MER), **P. Ricci**, Professor, **D. Testa**, Research and Teaching Associate – MOOC on *"Plasma Physics and Applications"*

The first MOOC to teach the basics of plasma physics and its main applications: fusion energy, astrophysical and space plasmas, societal and industrial applications

### **3.2 Master courses and laboratory given by SPC staff**

#### **Master courses given by SPC staff members**

**P. Ricci**, Associate Professor – *"Plasma physics II"*

One semester option course presented mainly to 4th year Physics students, introducing the theory of hot plasmas via the foundations of kinetic and magnetohydrodynamic theories and using them to describe simple collective phenomena. Coulomb collisions and elementary transport theory are also treated. The students learn to use various theoretical techniques like perturbation theory, complex analysis, integral transforms and solutions of differential equations.

**A. Fasoli**, Professor, **I. Furno**, Maître d'Enseignement et Recherche (MER), **A.A. Howling**, Research and Teaching Associate, **D. Testa**, Research and Teaching Associate – *"Plasma Physics III"*

An introduction to controlled fusion, presented as a one semester option to 4th year Physics students. The course covers the basics of controlled fusion energy research. Inertial confinement is summarily treated and the course concentrates on magnetic confinement from the earliest linear experiments through to tokamaks and stellarators, leading to the open questions related to future large scale fusion experiments.

**A. Fasoli**, Professor and **M.Q. Tran**, Professor - *"Nuclear fusion and plasma physics"*

The aim of this course is to provide a basic understanding of plasma physics concepts of fusion energy, and of the basic principles of fusion reactors, including the main technological aspects. This course was given within the frame of the Master in Nuclear Engineering.

## Advanced Physics Laboratory

During the Spring semester of 2016, SPC staff members have supervised 10 EPFL students performing their Advanced Physics Laboratory work. During the Autumn semester of 2016, we had 10 EPFL students and 3 exchange students.

## EPFL Master degrees awarded in 2016

Blondel Lily: *"Axisymmetry tokamak equilibria with a predefined Q-profile"*

Christen Nicolas: *"Exploring the effects of drifts in Single Null and Snowflake Divertors on TCV using UEDGE"*

Dupertuis Nathan: *"Correlation study between D'Angelo modes and drift waves in magnetized plasma with inhomogeneous density and flow"*  
(performed at Kyushu Univ./RIAM, Japan – Prof. S.-I. Itoh)

Filleul Félicien: *"Resonant-antenna based source for whistler plasma thrusters"*

Martens Paul: *"Arc mitigation methods for space applications"*

Pedro Michael: *"Robust statistical methods for plasma turbulence studies"*

## 3.3 Postgraduate courses given by SPC staff

**S. Brunner, and J.P. Graves** – *"Advanced Theory of Plasmas"*

This course is given to the Physics Doctoral School and covers: MHD equilibrium and stability in Tokamaks, Waves and instabilities in Inhomogeneous Plasmas, Introduction to Nonlinear Effects in Plasmas.

**J.P. Graves, J.-M. Moret, D. Testa, M.Q. Tran, O. Sauter, P. Ricci, A. Fasoli, U. Sheikh** - *"Magnetic confinement"*. This course is given to the Physics Doctoral School.

**Ch. Hollenstein, P. Bruzzone, S. Alberti, B. Duval, J.-P. Hogge, D. Fasel, Y. Martin, Ph. Spaetig, A. Howling, U. Sheikh** - *"Fusion and Industrial Plasma Technologies"*. This course is given to the Physics Doctoral School

**T.M. Tran**, *"MPI, an introduction to parallel programming"*, EPFL-DIT Section

**I. Furno, H. Reimerdes, B. Labit** - *"Plasma diagnostics in basic plasma physics devices and tokamaks: from principles to practice"*. FUSENET course.

**J.-M. Moret, F. Felici** (Eindhoven Univ., NL) - *"Control and Operation of Tokamaks"*. FUSENET course.

### 3.4 *Doctorate degrees awarded during 2016*

**Falk BRAUNMUELLER:** *"Nonstationary operating regimes in Gyrotron oscillators"* (EPFL Thesis 6959(2016))

Gyrotrons belong to the family of high-power coherent radiation sources known as Electron Cyclotron Masers (ECMs) and are based on the physical mechanism of the ECM-instability, converting electron rotational kinetic energy into coherent electromagnetic radiation. The worldwide gyrotron R&D; is mainly driven by the application in heating a magnetically confined fusion plasma, which requires coherent radiation sources with MW power-level in the sub-THz frequency range. In the last two decades, an application for gyrotrons emerged in the field of Nuclear Magnetic Resonance (NMR) spectroscopy, where a dramatic enhancement in sensitivity can be achieved via Dynamic Nuclear Polarization (DNP), requiring a low-power (1-10W), sub-THz frequency (<200GHz) coherent radiation. The subject of this thesis is a gyrotron prototype developed at SPC/EPFL for the DNP-application. It is designed for continuous mode (CW)-operation on the TE<sub>7,2</sub>-mode and has a maximum radio-frequency (RF)-power of P=150W at a frequency of f=260.5GHz. The DNP-gyrotron has demonstrated to be an ideal test-bench for fundamental research on the beam-wave interaction process. The weakly overmoded gyrotron cavity is such that transverse mode competition can be neglected and the studied dynamical regimes concentrate on the 1D-longitudinal dynamics. The main topic of this work concentrates on the experimental measurements and numerical modeling of novel non-stationary regimes, characterized by a multi-frequency spectrum and a modulated RF-power. These experimental results have shown that the very fast dynamics (nanosecond time-scale) observed in non-stationary regimes is such that the usual assumption, in which the cavity electromagnetic field is not varying during the electron time of flight, is no more valid. To overcome this assumption a new model based on a Particle-In-Cell (PIC) approach has been developed and a new code TWANG-PIC has been written and successfully exploited. Also, the linear regime has been revisited from the theoretical point of view by developing a new moment-based model. Based on this model a new code TWANGLIN has been written and used for a detailed analysis of the experimentally measured threshold conditions (starting current) covering operating points from forward to backward-wave gyrotron regimes. Among a large variety of non-stationary regimes, that is described and analyzed, a novel specific nanosecond-pulsed regime was studied, in which the multi-frequency spectrum consists of frequency-equidistant, phase-locked sidebands. This novel regime may open up new applications for gyrotrons. For the first time it has also been possible to experimentally investigate, and model via numerical simulations, the dynamical properties from the linear regime up to chaotic regimes. The numerical simulations with TWANG-PIC are in good qualitative agreement with the experimental results and showed that the observed non-stationary regimes are associated to non-linear axial mode-competition. Another important task was to configure the gyrotron for the DNP-NMR spectroscopy application. Several state-of-the-art features have been included, such as a continuous frequency-tuning over 1.2GHz by varying several control parameters simultaneously, a fast (<15kHz) frequency-modulation over 100MHz and a feedback-controller for stabilizing RF-parameters. Currently the gyrotron is routinely and successfully operated on a 400MHz DNP-NMR experiment.

**Julien DOMINSKI:** *"Development of an arbitrary wavelength solver in ORB5"*  
(EPFL Thesis 7286(2016))

In tokamak fusion plasmas, micro-turbulence transport is known to be the cause of large losses of heat and particles. The present work deals with the study of electrostatic micro-turbulence transport driven by instabilities of essentially two types: the ion temperature gradient (ITG) modes and the trapped electron modes (TEM). The plasma is described within the gyrokinetic framework, which permits to save computational resources compared to the classical Vlasov kinetic description. In gyrokinetic simulations of fusion plasmas, the passing electrons are often assumed fast enough so that they respond instantaneously to the electrostatic perturbations. In this case, their response is computed adiabatically instead of kinetically. The main advantage is that this simplified model for the electron response is less demanding in computational resources. This assumption is nonetheless incorrect, in particular near mode rational surfaces where the non-adiabatic response of passing electrons cannot be neglected. This thesis work focuses on the study of this passing electron non-adiabatic response, whose influence on microturbulence is studied by means of numerical simulations carried out with the gyrokinetic codes GENE and ORB5. In the first part of this thesis work, the response of passing electrons in ITG and TEM microturbulence regimes is studied by making use of the flux-tube version of the GENE code. Results are obtained using two different electron models, fully kinetic and hybrid. In the hybrid model, passing particles are forced to respond adiabatically while trapped are handled kinetically. Comparing linear eigenmodes obtained with these two models enables one to systematically isolate fine radial structures located at corresponding mode rational surfaces, clearly resulting from the non-adiabatic passing-electron response. Nonlinear simulations show that these fine structures on the non-axisymmetric modes survive in the turbulent phase. Furthermore, through nonlinear coupling to axisymmetric modes, they induce radial modulations in the effective profiles of density, ion and electron temperature and zonal flows  $E \times B$  shearing rate. Finally, the passing-electron channel is shown to significantly contribute to the transport levels, at least in our ITG case. Also shown is that the passing electrons significantly influence the  $E \times B$  saturation mechanism of turbulent fluxes. Following this study in flux tube geometry, the influence of the non-adiabatic passing electron response near mode rational surfaces is further studied in global geometry with the global gyrokinetic code ORB5, in which a new field solver is implemented for the gyrokinetic quasi-neutrality equation valid at arbitrary wavelength, overcoming the former long wavelength approximation made in the original version of the code. A benchmark is conducted against the global version of the gyrokinetic code GENE, showing very good agreement. Nonlinear simulations are carried out with the new solver in conditions relevant to the TCV tokamak, with the physical deuterium to electron mass ratio ( $m_i/m_e=3672$ ) and are compared to simulations carried out with heavy electrons ( $m_i/m_e=400$ ). The particular spectral organization of the passing electron turbulent flux and its dependence on the radial profile of the safety factor are revealed. In particular, the formation of short-scale transport barriers is studied near low-order mode rational surfaces. Results show that quantitatively correct nonlinear fully-kinetic simulations of tokamak transport must be carried out in a full torus and with the physical mass ratio.

**Natalia GLOWA:** *"Quench detection and protection of the HTS insert coil"*  
(EPFL Thesis 6712(2016))

As a result of extremely high upper critical fields  $B_{c2}$ , high temperature superconductors (HTS) have the potential to be used as high field insert coils in magnet systems where the background field is provided by low temperature superconductors (LTS) with the aim of application of such systems for high energy physics, nuclear magnetic resonance and energy storage. Among the



superconductors discovered in late 1980s, one that is widely studied is YBCO coated conductor (CC). Despite the advanced 2G conductor technology in recent years allowing for manufacturing of long lengths of YBCO CC, up to 1 km, the crucial issue in practical application of the hybrid systems with YBCO insert coil remain the quench detection and protection of the insert. Unlike in LTS magnets, the quench propagation in HTS is significantly slower, which makes quench detection and consecutively protection, very challenging. Following a new approach for quench protection a non-insulated HTS insert coil was manufactured at the SPC. In case of quench, the current is expected to by-pass the normal zone and prevent the coil from a permanent damage. The idea of non-insulated free-standing coils has been already studied and brought promising results in terms of self-protection of such coils. However, in a hybrid system of LTS-HTS, the quench behaviour needs careful evaluation that includes magneto-thermo-electrical study. The objective of this work is to study and discuss the applicability of HTS insert coils (insulated and non-insulated) by addressing the issue of their quench detection and protection schemes. The starting point for the analysis is studying the existing design according to SPC specifications taking into account various operating modes together with detection and protection schemes. Finally, general guidelines for the design of a successful LTS-HTS magnet system will be discussed.

**Gabriele MERLO:** *"Flux-tube and global grid-based gyrokinetic simulations of plasma microturbulence and comparisons with experimental TCV measurements"* (EPFL Thesis 7065(2016))

In magnetic fusion devices, the radial transport of heat and particle largely exceeds predictions based on collisional processes. This is widely understood as a consequence of small-scale turbulence which results from the nonlinear behaviour of so-called microinstabilities. The complexity of such nonlinear phenomena allows one to address microturbulence only with a numerical description, carried out here within the gyrokinetic framework. This reduced kinetic model describes the evolution of the particle distribution functions and of the self-consistently generated electromagnetic fields neglecting the fast gyromotion. In this work we applied the grid-based gyrokinetic code GENE, using both its local and global versions, to model some of the experimental observations made in the Tokamak à Configuration Variable (TCV) at the Swiss Plasma Center. All simulations are performed considering realistic magnetic geometries, in turn provided by the MHD equilibrium solver CHEASE. In order to verify the interface of GENE with CHEASE, a series of benchmarks have been developed and successfully carried out in the linear local limit. These tests have then been extended to the global version of the code and a good agreement found with results obtained with the gyrokinetic Particle In Cell code ORB5. A significant part of this work deals with the electron heat confinement improvement observed when the shape of the plasma is modified by changing the sign of the edge triangularity, from positive to negative. In the latter case, half the heating power is required to maintain the same electron profiles compared to the former, which was experimentally interpreted as a better confinement at all radial locations, even though triangularity has a finite radial penetration depth. A series of local runs were carried out to investigate the dependence of profile stiffness on shaping, failing at reproducing both the absolute level of transport as well as the ratio between the two shapes. Global gradient-driven simulations have then been performed, showing a very high sensitivity of the electron heat flux with respect to the density gradient. These runs, carried out neglecting carbon impurities, are compatible with the experiments when using parameters from an experimentally well diagnosed discharge. In this case, strong global effects which lower the heat flux compared to local runs are seen. Local and global simulations have then been performed looking at axisymmetric dynamics in the frequency range of the Geodesic Acoustic Mode (GAM). Experimentally, the GAM is almost always observed as a

radially coherent mode, i.e. an oscillation at constant frequency over a main fraction of the plasma minor radius. The only exception is for very large values of the edge safety factor  $q$ , where the mode loses its coherence becoming dispersive. A density ramp-up was studied with local simulation, already obtaining a reasonable agreement with measurements of heat transport as well as GAM frequency and amplitude. The coherent GAM was then investigated with global runs. Simulations qualitatively agree with experiments and a good match is recovered with ORB5 results when the same physical model is used. Finally, the hypothesis of a coherent-dispersive GAM transition related to the safety factor profile is addressed. It is found that changing only  $q$  is not sufficient to induce a regime transition, which thus appears to be due to other parameters, including finite machine size effects.

### **3.5     *Ph.D. Theses supervised by SPC staff ongoing at the end of 2016***

**Riccardo AGNELLO:** *"Helicon plasma source for negative-ion beams"*

For future fusion reactors such as DEMO, a new generation of Neutral Beams able to deliver high energies and high powers will be required. Using negative ion beams as a source is a promising technology to reach the expected performances. At the SPC a new helicon plasma source based on a resonant antenna is being developed for this purpose. The thesis work consists in the characterization of helicon plasmas by many diagnostics, such as optical emission spectroscopy, magnetic probes, and, in particular, a microwave interferometer. These approaches are crucial to determine the efficiency of negative ions extraction on which the performance of the neutral beam is strictly related.

**Himank ANAND:** *"Exploration of candidate fusion reactor regimes by real time control of tokamak plasma shape"*

The majority of the work done in the year 2016 was devoted to the refinement, generalization and completion of a fully developed time-dependent plasma shape and position control algorithm with the capability of controlling time-varying shape scenarios, and to its experimental implementation on various plasma configurations. The controller was successfully commissioned for various limited and diverted plasma scenarios.

**Carrie BEADLE:** *"Investigation of plasma turbulence in diverted SOL"*

I started my PhD in the edge physics group in September 2016. I will study turbulent transport in the plasma scrape-off layer in a diverted geometry using the GBS simulation code. So far I have been learning about the plasma model used by GBS and how the diverted geometry is implemented in the code.

**Nikolay BIKOVSKIY:** *"HTS high current cable for fusion application"*

Research activities in 2016 were aimed at better understanding the results obtained from the test in EDIPO of the HTS cable prototypes. The main issue arising from the measurements is the performance degradation of the prototypes in the cycling test. A detailed inspection allowed us to conclude that the transverse cyclic load is the key factor of the degradation. Based on the obtained data, two designs of 53kA/18T cable for the Tokamak Central Solenoid coil have been proposed for test in SULTAN.

**Francesco CARPANESE:** *"Fast tokamak simulator coupling equilibrium and surface averaged transport for pre-discharge analysis and real time application"*

The project aims to develop a fast "tokamak simulator" able to solve self-consistently the equilibrium and surface-averaged transport system of equations possibly in real time for ITER relevant resistive time scales. The first step will be coupling the equilibrium code LIUQE and the transport code RAPTOR. The free equilibrium & predictive transport platform would be useful to test and tune real-time controllers, pre-discharge analysis and as a real-time observer.

**Ajay CHANDRARAJAN JAYALEKSHMI:** *"Gyrokinetic simulations of turbulent transport with the GENE code"*

This PhD research project involves the study of turbulent transport in tokamak plasmas using the grid-based gyrokinetic code GENE. More specifically, research will be devoted to the study of structures near mode rational surfaces, starting with convergence studies of nonlinear simulations with kinetic electrons.

**Oulfa CHELLAI:** *"Study of mm-wave scattering by edge-localised turbulence in magnetically confined plasmas"*

The propagation of mm-wave in turbulent plasmas is of outmost importance in tokamaks because it could lead to diffraction of the beams by the perturbations. This year, experiments were run on TORPEX to identify the effect of isolated blobs on mm-beams. Numerical simulations run on COMSOL have shown good agreements with the experiments. The propagation of the X3 beams were characterised in the vacuum and we started to investigate the effect of the plasma on the beam profiles.

**Dahye CHOI:** *"Suprathermal electron physics in TCV"*

Fokker-Planck modeling of TCV ECH/ECCD pulse discharges has been performed using the code LUKE. The time evolution of the electron distribution function in a short time scale is simulated and HXRS synthetic diagnostic has been computed. The HXRS detector's response function has been modeled and implemented in the synthetic diagnostic code.

**Jonathan FAUSTIN:** *"Self-consistent interaction of fast particles and ICRH waves in 3D applications of fusion plasma devices"*

The loss channels acting on fast particles in the Wendelstein 7-X stellarator were assessed and reported. It was also found that the high plasma density hinders the formation of a significant fast ion population. Our simulations, using the SCENIC code package, showed that realistic ICRF minority heating schemes (in terms of RF power and minority concentration) are not suited for generating large fractions of fast ions. On the other hand, SCENIC simulations show that a larger fast ion population can be generated if the three-ion species scheme is applied.

**Matteo FONTANA:** *"Turbulence studies in TCV using Correlation ECE diagnostics"*

During 2016 the Correlation ECE diagnostic has been extensively used to take electron temperature fluctuations measurements in a wide variety of plasma discharges, in particular in the frame of the MST1 campaign. Gyrokinetic linear simulations have been run with the code GENE to look for changes in turbulence regime in experimental shots.

**Jérémy GENOUD:** *"Advanced models for wave-particle interaction in gyrotrons"*

The development of the linear and spectral code TWANGlinspec describing the self-consistent wave-particle interaction in a gyrotron oscillator has been pursued. It includes the implementation of a new finite element method for the spatial discretization and of parallelization based on a Message Passing Interface

(MPI), which are necessary to study spurious instabilities in high-power gyrotron beam-ducts. Furthermore, the possibility to study start-up scenarios in gyrotrons has also been implemented and a comparison with measurements from the 1.5MW, 110GHz MIT-gyrotron has been completed.

**Zhouji HUANG:** *"Experimental study of plasma turbulence in the TCV tokamak"*

Experiments were performed to measure density fluctuations by Tangential Phase Contrast Imaging (TPCI) in plasmas with same profile but different ECH input power in positive and negative triangularity. Oscillations at or near the frequency of Geodesic Acoustic modes (GAM) were studied in SOL by edge diagnostics in divertor plasmas under various divertor configurations.

**Rogério JORGE:** *"ISTTOK Scrape-off Layer Turbulent Regimes"*

Turbulence in the Scrape-off Layer (SOL) region of magnetic confinement fusion devices is still a major topic of research in today's plasma physics studies. This year, a thorough comparison between the GBS code from EPFL and experimental results of ISTTOK's (IST Tokamak) SOL was performed, where we also assessed the main driving instabilities and turbulence saturation mechanisms. Also, to better understand the plasma properties in a low mean-free path regime, a hybrid fluid-kinetic model was derived that evolves the moments of the distribution function based on a full-f drift-kinetic description, with full Coulomb collisions.

**Andreas KLEINER:** *"Nonlinear resistive MHD modelling of tokamak stability limits"*

The nonlinear evolution of MHD instabilities has been investigated in several contexts. The impact of coupling of infernal modes to neoclassical tearing modes was evaluated from numerical simulations with the initial value code XTOR-2F with and without consideration of the bootstrap current. The model of linear infernal modes has been extended to the nonlinear regime. Further research was focused on saturated nonlinear external kink modes in the context of plasma edge perturbations observed experimentally and in numerical simulations.

**Mengdi KONG:** *"Real-time control of NTMs in TCV"*

My work has focused on the optimization of NTM (neoclassical tearing mode) stabilization and preemption using EC (electron cyclotron) beams in 2016. The NTM control experiments have been done in both a feed-forward and a feedback way. In the experiments, I demonstrated the control schemes used and studied the effects of various parameters (such as density, EC power and misalignment) on the triggering, stabilization and preemption of NTMs. I have also upgraded the real-time NTM controller in TCV and moreover added a supervision algorithm to do integrated real-time control experiments.

**Samuel LANTHALER:** *"Higher-order guiding centre motion"*

Higher-order Larmor radius corrections to the guiding-centre equations have been considered for the modelling of fast particle distributions. In the case of neutral beam injection in a MAST-like equilibrium, such corrections have been found to lead to significant differences in the predicted fast ion current, as well as the fast ion losses due to the interaction with resonant magnetic perturbations (RMP).

**Emmanuel LANTI:** *"Porting of a gyrokinetic PIC code to many- and multi-core platforms and its application to global flux-driven microturbulence transport simulations in tokamaks"*

In its previous version, the ORB5 field solver was able to solve the gyrokinetic quasi-neutrality equation in its integral form, using the long wavelength approximation, or using the Padé approximation. In the latter case, only the fully kinetic electron model was considered. It has now been extended such that the

Padé approximation is able to also treat adiabatic electrons and the hybrid electron model where the trapped particles are considered to be kinetic while the passing ones are considered to respond adiabatically. With this extension ORB5 is now able to simulate short-scale instabilities, similarly to the integral solver, but at a lower cost.

**Fabian MANKE:** *"Fast-ion transport phenomena in turbulent toroidal plasmas"*

After completing the installation of a second Langmuir-probe array on TORPEX, spatio-temporal ('secondary') modes on the blob-contours were sought. The concepts for a new phosphorescent probe for potentially higher resolutions proved promising in first tests. While familiarising in depth with fractional diffusion models for fast-ion transport, the corresponding experiments have been resumed on TORPEX with continuing improvements to electronics and software. Recent fast-ion time-traces show signs of intermittency after passing from a super- into a sub-diffusive transport phase. This behavior had never been observed before experimentally to our knowledge.

**Claudio MARINI:** *"Poloidal Charge Exchange (CX) plasma rotation diagnostic in TCV"*

The emission line intensities of H<sub>2</sub> and D<sub>2</sub> on RAID were analysed with the help of the collisional radiative code YACORA. A Fast Ion D-Alpha (FIDA) diagnostic was implemented and used to study the fast ions generated in TCV by the newly installed 1-MW NBH. The edge Charge eXchange Recombination Spectroscopy (CXRS) system was commissioned and used in the study of momentum evolution across sawteeth in TCV.

**Roberto MAURIZIO:** *"Infrared measurements of the heat flux spreading under variable divertor geometries in TCV"*

"The main goal of the thesis is to improve the understanding of plasma Scrape Off Layer (SOL) transport physics via characterisation of the divertor heat loads for a wide range of operational scenarios in TCV. The main experimental tool is the recently upgraded Infrared (IR) Thermography system of TCV, featuring two fast IR cameras. The investigation has involved so far mainly attached L-mode plasmas, in multiple divertor geometries: the conventional Single-Null, the Snowflake, the X-Divertor. Such work will soon be extended to H-mode plasmas, for both transient and stationary heat loads, and to detached regimes."

**Pedro MOLINA:** *"IR camera measurements of heat loads in plasma-facing components"*

A Doppler back-scattering reflectometer was implemented and tested in TCV using a fast arbitrary waveform generator (25GHz BW) and vector-network-analyzer extension modules from VDI. Amplifiers, IF filters, and an IQ mixer were used to digitize Doppler shifts in WR-15. Poloidal rotation velocities of turbulent electron waves are available with ms resolution. In parallel, short pulse reflectometer developments demonstrated that 1ns pulses could be generated with minimal distortion using the same AWG and extension modules.

**Federico NESPOLI:** *"Scrape Off Layer physics in different magnetic configurations in TCV"*

During the last year I coordinated two experiments in the MST1 campaign, TCV15-2.2-4 and TCV15-He-13, on the Scrape-Off Layer (SOL) power width in limited configuration, studying the physics governing the formation of the near/far SOL. Also, I implemented the tools to perform blob detection and tracking on GBS simulations of the TCV SOL. Finally, the last part of the year was devoted to the writing of my PhD thesis.



**Noé OHANA:** *"Development of a gyro-kinetic PIC code for new HPC architectures"*

During this year, I pursued the development of an optimized and modular platform for gyrokinetic Particle-in-Cell (PIC) codes running on different hybrid architectures. I focused on the GPU version and measured the gain that can be obtained with respect to classical CPUs. I also took care of the parallel scalability at large scale (thousands of compute nodes) and came up with a new scheme reducing the amount of transferred data in parallel Fourier transforms. Moreover, I implemented an alternative representation for the fields in Fourier space. I am currently comparing the precision and efficiency of this new method with the classical one.

**Paola PARUTA:** *"Advanced numerical algorithm for the simulation of the scrape off layer plasma turbulence"*

Simulating the most external plasma region of a tokamak, the scrape-off layer (SOL), is of crucial importance in the way towards a fusion reactor. In the last few years a numerical code, GBS, has been developed for solving the drift-reduced Braginskii equations, and describe turbulence in the tokamak SOL. In the past year, I have re-formulated these equations in a general form that enables to treat diverted configuration with X-point and the first simulations with X-point were successfully performed in GBS.

**Hamish PATTEN:** *"Advanced three-dimensional Ion Cyclotron Resonance Heating phenomena"*

Applying the SCENIC code package to aid JET experiments and tasks, a variety of different ICRF and NBI heating scenarios were simulated and compared against other codes (SELFO, PION, etc). Important differences were investigated via studying the influence of toroidally localising the ICRF antenna on the RF-pinch effect. Additionally, the VENUS-LEVIS NBI beam module (part of the SCENIC code package) was updated to handle 3D configurations via the method of voxelisation (volume pixelisation). Thus realistic WVII-X stellarator NBI beam geometry benchmarking simulations were carried out with codes such as ASCOT, ANTS, BEAMS3D, BBNBI, etc.

**Federico PESAMOSCA:** *"Magnetic real-time control of tokamak plasmas"*

The PhD started in October 2016 and with an exchange period (mission) at TU/e, Eindhoven (Netherlands), to work in daily contact with the co-advisor for the PhD, Dr. Federico Felici, responsible for the first part of the project. In this way it was possible to start working on the fundamentals of control of plasma shape and position in the TCV tokamak.

**Masuhudan RAGHUNATAN:** *"Guiding-centre particle orbits for 3D equilibria with rotation"*

We studied the effect of 3D deformations on the bootstrap current and impurity transport through the use of neoclassical theory of transport. The first topic focuses on the computation of the background electron bootstrap current considering magnetic equilibria with a 1/1 saturated internal kink through neoclassical theory. The second part involves the study of the confinement and transport of heavy impurity ions, namely tungsten. Including plasma rotation and friction force, strongly responsible for the confinement of impurities in a plasma, is done additionally through neoclassical theory and then included in the VENUS-LEVIS particle orbit-following code.

**Fabio RIVA:** *"Verification and Validation of SOL plasma turbulence codes"*

During the last year, an analytical model to express the magnetic field dependence on elongation, triangularity, and Shafranov shift was implemented in the GBS code, allowing the investigation of the effects of plasma shaping on scrape-off layer turbulence. Moreover, the method of manufactured solutions, previously used to

rigorously verify GBS, was generalized to particle-in-cell (PIC) codes, allowing us to verify a PIC simulation.

**Joyeeta SINHA:** *"Improvement of the plasma formation and its application for the doublet shaped plasma creation on TCV"*

Successful simultaneous breakdown was obtained at the top and bottom of the vessel by using only inductive plasma start-up for the development of the doublet shaped plasma scenario in TCV. Before the top plasma merged with the bottom plasma, the two plasmas could survive up to 20ms with  $I_p$  of 50kA each. Implementation of the bump-less transfer control technique for the radial position and  $I_p$  feedback control to improve the single-axis plasma formation in TCV was tested experimentally.

**Lorenzo STIPANI:** *"Analysis of the interaction between fast ions and MHD instabilities and turbulence on the TCV tokamak"*

The focus, for the beginning of this PhD project, was on the diagnostic techniques implemented at TCV for magnetic measurements (MHD equilibria and fast modes) and for fast-ion dynamics such as detection of neutral particles by means of NPA/CNPA device.

**Anna TEPLUKHINA:** *"Ramp-down simulation and optimization of TCV and AUG plasmas"*

The development of the RAPTOR transport model was continued and a new adhoc transport model for electron heat diffusivity has been implemented. Results of full TCV and AUG discharge simulations have been successfully verified via comparison with the experimental data. Numerical optimization of H-L transition, plasma current and elongation shows that fast decrease in elongation allows fast ramp-down in plasma current while keeping internal inductance at safe levels. Early H- to L-mode transition reduces the drop in poloidal beta which can be important for plasma MHD stability and control.

**Mirko WENSING:** *"Boundary modelling of conventional and alternative divertor configurations in TCV"*

This PhD work aims at investigating the potential of advanced divertor configurations, of interest for DEMO. At present, the work is focused on the preparation of the TCV divertor upgrades, in particular on the assessment of the advantages in installing up to three new divertor coils to increase the gradient of the poloidal magnetic field at the x-point of diverted TCV plasmas. The investigation will also yield requirements for the placement of the coils and their current capability. The calculations are carried out using the new Matlab version of the FBT equilibrium code.

**Kevin VERHAEGH:** *"Divertor spectroscopy on TCV"*

Work has been done on further development of the new Divertor Spectroscopy System (DSS) on the TCV tokamak. New techniques for analyzing Balmer line spectra have been developed, allowing for improved estimates on electron density, recombination and ionization rates. DSS measurements have been important for MST1 detachment experiments and have shown that the detachment front in TCV stays near the target during density ramp discharges, which is in contrast with observations at higher density tokamaks.

**Christoph WERSAL:** *"The interaction between neutral atoms and turbulent plasma in the tokamak scrape-off layer"*

In 2016, I finalised the study of the dependence of the electron temperature along the magnetic field line in a limited tokamak SOL by comparing self-consistent turbulent simulations of plasma and neutrals with a refined two-point model.

Furthermore, I worked on studying the impact of neutral density fluctuations on gas puff imaging. It turns out that the neutral density strongly fluctuates, and its fluctuations are anti-correlated with respect to the plasma fluctuations.

## **4 COMMUNICATION ACTIVITIES IN 2016**

The SPC has been strongly committed in the general EPFL Open Doors held on 5-6 November. Both TCV and TORPEX halls were open to the public and SPC guides have tirelessly introduced the visitors to plasma and fusion and showed them the different installations. In addition, a new presentation of the domain was turning in loop, and some didactic experiments have given the opportunity to familiarize with some plasma physical concepts. Eventually, conferences on plasma and fusion were given repeatedly.

Beside these open doors, more than 80 groups totaling more than 2900 children, teenagers, students or adults visited the center. Several outreach papers and presentations were carried out.

## 5 FUSION & INDUSTRY RELATION

Since 2009 the Swiss industry benefits from the services of an Industry Liaison Officer (ILO) to support procurement opportunities that arise in the course of the construction of the ITER Experimental Fusion Reactor.

The ITER ILO activity is integrated in a marketing structure named Swiss ILO ([www.swissilo.ch](http://www.swissilo.ch)) in charge to support the Swiss Industry in seven large-scale International Research Organisations. Besides ITER, these are CERN, ESO, ILL, ESRF, XFEL and ESS. The mandate taken by the Swiss Plasma Center to host the Swiss ILO Office was renewed for an additional period of four years (2017-2020).

The Swiss industry is known for having unique worldwide technology selling points. The ability of many Swiss companies to sell core technologies to different research organisations, e.g. in the fields of cryogenics, vacuum, metrology, optics or RF components, was largely demonstrated in the past years.

In the category of component based suppliers, revenues in 2016 at ITER continued to be generated typically from VAT (vacuum valves), LEICA HEXAGON (laser based metrology systems), and COMET (high voltage RF capacitors).

A second category of Swiss suppliers is made of system engineering houses currently executing large single shot contracts for ITER.

AMPEGON (*High Voltage Power Supply converters*) has manufactured the first power supply unit within the F4E ECRH Modulator Program. The *Factory installation* review was completed in 2016 and the manufacturing of two further units is scheduled for 2017.

LINDE KRYOTECHNIK (*Helium compressor based cryogenic systems*) started in 2016 to execute the ITER *Cryodistribution Project*, the largest Swiss contract on ITER (>30 M), headed by ITER India. This contract has three main elements: the *Cryoplant Termination Cold Box (CTCB)*, which links the helium refrigeration plant with the cryogenic transfer lines to the Tokamak building, the *Auxiliary Cold Boxes (ACBs)*, and the *Thermal Shield Cooling Systems (TSCS)*, which support the distribution of the various cryogenic streams within the ITER Tokamak building. Various design reviews and engineering tasks were successfully completed in 2016. The production phases will continue through 2019.



## APPENDICES

### *APPENDIX A Articles published in Refereed Scientific Reviews during 2016*

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## **APPENDIX B Conferences and Seminars**

(see SPC archives at <http://crppwww.epfl.ch/archives>)

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**T. Tala, C. Chrystal, R.M. McDermott, S-P. Pehkonen, A. Salmi, C. Angioni, M. Barnes, B. Duval, C. Giroud, B. Grierson, W. Guttenfelder, J. Ferreira, J. Hillesheim, S. Kaye, P. Mantica, M. Maslov, S. Menmuir, F. Parra, C. Petty, T. Pütterich, J.E. Rice, F. Ryter, W. Solomon, G. Tardini, M. Tsalas, H. Weisen, M. Yoshida, JET contributors, the ASDEX-Upgrade team, the DIII-D team, the NSTX team, the EUROfusion MST1 Team and the ITPA Transport & Confinement Topical Group,** Multi-Machine Experiments to Study the Parametric Dependences of Momentum Transport and Intrinsic Torque, 43rd European Physical Society Conference on Plasma Physics, Leuven, Belgium, 4-8 July 2016, Vol 40A, O2.104 (2016).

**H. Patten, J.P. Graves, J. Faustin, S. Lanthaler, D. Van Eester, E. Lerche, T. Johnson, JET Contributors,** Modelling the Fast-ion RF-Pinch Effect with a Toroidally Localised ICRF Antenna, 43rd European Physical Society Conference on Plasma Physics, Leuven, Belgium, 4-8 July 2016, Vol 40A, P2.008 (2016).

**P. Ricci, J. Morales, F. Nespoli, P. Paruta, F. Riva, C. Wersal, J.A. Boedo, I. Furno, F.D. Halpern, B. Labit, J. Loizu, S. Jolliet, R. Jorge, A. Masetto, C. Tsui,** the TCV Team, and the EUROfusion MST1 Team, Progress in simulating SOL plasma turbulence with the GBS code, 43rd European Physical Society Conference on Plasma Physics, Leuven, Belgium, 4-8 July 2016, Vol 40A, P4.028 (2016).

**C. Wahlberg, J.P. Graves,** Perturbed vacuum magnetic field and global  $m=2$  components associated with geodesic acoustic modes in tokamaks, 43rd European Physical Society Conference on Plasma Physics, Leuven, Belgium, 4-8 July 2016, Vol 40A, P2.046 (2016).

**H. Weisen**, *Neutron Yield Studies in JET H-Modes*, 26th IAEA Fusion Energy Conference, Kyoto, Japan, October, 17-22, 2016 (2016).

## **B.2      Seminars presented at the SPC in 2016**

**Dr. A. Stegmeir**, Max-Planck-Institut für Plasmaphysik, Garching, Germany, *"GRILLIX: A 3D turbulence code for magnetic fusion devices based on a field line map"*

**Dr. M. Blank**, Communications & Power Industries (CPI), Palo Alto, CA, USA, *"High Power and High Frequency Gyrotron Development at CPI"*

**F. Braunmueller**, SPC-EPFL, *"Gyrotron physics from linear to chaotic regimes: experiment and numerical modeling"*

**C. Beadle**, Univ. of Cambridge, UK, *"Rigorous verification of Particle-in-Cell codes"*

**Prof. H. Tang**, Space Plasma & Electric Propulsion Laboratory, School of Astronautics, Beihang University, *"Electric/Plasma Propulsion Research in SPEPL"*

**Prof. T. Fulop**, Chalmers University of Technology Goteborg, Sweden, *"Flows and avalanches in plasmas"*

**S. Polishchuk**, Taras Shevchenko National University of Kyiv Kyiv, Ukraine, *"Influence of scattering efficiency and dye concentration on random lasing parameters in vesicular polymeric films"*

**M. Wensing**, Aachen University Aachen, Germany *"Reaction-diffusion modelling of hydrogen in beryllium"*

**A. Palha**, Eindhoven University of Technology, NL, *"Mimetic spectral element discretization of the Grad-Shafranov Equation"*

**Prof. N. Marzari & A. Cepellotti**, National Centre for Competence in Research NCCR MARVEL, EPFL, *"Boltzmann in materials - tales of heat and electricity, the death of phonons, and the birth of relaxons"*

**G. Scionti**, Univ. Milano-Bicocca, I, *"Neutronic design for an irradiation test station at ESS for fusion material studies"*

**Dr. I. Pagonakis**, IHM-KIT-Karlsruhe, D, *"Progress and recent advances in gyrotron theory and design"*

**Dr. T. Stange**, Max-Planck-Inst. für Plasmaphysik, Greifswald, D, *"First ECRH plasmas in the Wendelstein 7-X Stellarator"*

**Dr. T. Stange**, Max-Planck-Inst. für Plasmaphysik, Greifswald, D, *"High-power and microwave engineering for Electron Cyclotron Resonance Heating (ECRH) systems: Protection and RAMI studies"*

**G. Merlo**, SPC-EPFL, *"Flux-tube and global GENE simulations of microturbulence and comparisons with TCV measurements"*

**A. Pau**, Univ. degli studi di Cagliari, I, *"Development of a multi-machine disruption analysis tool for automatic database construction"*

**F. Pesamosca**, Politecnico di Milano, I, *"A model for dynamical oscillations in magnetically confined fusion plasmas at the transition to high confinement"*

**G. Verdoolaege**, Dept. of Applied Physics, Royal Military Academy, Brussels, B., *"Robust analysis of trends in fusion data using a simple probabilistic technique"*

**S. Wang**, Univ. of Science and Technology, Hefei, P.R. China, *"Magnetic plasma control analysis, design and validation using linear and non-linear models on the KTX and EAST devices"*

**L. Stipani**, Univ. Pisa, I, *"Phase mixing flow in a drift-kinetic collisionless plasma. The case of a kinetic passive scalar"*

**T. Goossens**, KU Leuven, Belgium, *"Decoupling multivariate polynomials in nonlinear system identification: the tensor approach"*

**Dr. T Vu**, CEA-Cadarache, F, *"Port-Hamiltonian approach for TCV – Current profile control"*

**Dr. F. Reimold**, Forschungszentrum Jülich, Inst. für Energie- und Klimaforschung – Plasmaphysik, Jülich, D, *"H-Mode Detachment Studies in ASDEX Upgrade with Experiment and Modeling"*

**M. Alija**, Technical University of Dortmund, *"Modeling and experimental investigations on the DC conductivity of crosslinked polyethylene specimens with layer thickness in the mm range for HVDC cables"*

**Prof. E. Scime**, West Virginia Univ., Morgantown, USA, *"Velocity Distribution Function Measurements in Low Temperature Plasmas"*

**T. Ravensberger**, TU/e, Eindhoven, NL, *"Control-oriented modelling of plasma breakdown and burn-through in TCV"*

**X. Chen**, General Atomics, San Diego, CA, USA, *"Recent Progress in Quiescent H-mode (QH-mode) Research on DIII-D Tokamak"*

**A. Pankin**, Lawrence Livermore National Lab., USA, *"Recent Progress Towards Integrated Modeling of Plasma Edge in Tokamaks"*

**M. Garnung**, Univ. Orléans, F, *"Analysis of high-resolution spectro-polarimetric data of the solar atmosphere"*

**F. Mentgen**, KIT, Karlsruhe, D *"Design studies towards a 140 GHz, 1.5 MW CW gyrotron (In view of an upgrade of the ECRH system at the W7-X stellarator)"*

**H. De Oliveira**, Etudiant EPFL, *"Polyesters synthesized from suberin monomers extracted from cork"*

**Dr. O. Février**, CEA-Cadarache, F, *"MHD simulations of magnetic island stabilization"*

**Dr. H. Gorji**, AICES, RWTH Aachen, Univ., Dept. of Mathematics, Aachen, D, *"Fokker-Planck description of fluid flows: efficient particle Monte-Carlo schemes for gases"*

**Dr. S. Pamela**, Culham-CCFE, UK, *"Simulations of ELMs with the JOREK code and comparison to experiments"*

**M. Zanini**, Univ. Padova, I, *"First extraction and acceleration operations of negative ion beams produced in NIO1 experiment"*

**Prof. J. Blum**, Université Côte d'Azur, CNRS, INRIA, Laboratoire J.-A. Dieudonné, Nice, France, *"The use of optimal control theory for equilibrium Identification and optimization of plasma scenarios"*

**Prof. T. McIntyre**, School of Mathematics and Physics, Faculty of Science, The University of Queensland, Brisbane, Australia, *"Ablation-radiation coupling measurements in a super-orbital expansion tube facility"*

**Prof. G. Lapenta**, KU Leuven, B, *"Turbulence and Reconnection"*

**Dr. J. Dominski**, SPC-EPFL, *"Development and application of Eulerian and Particle-In-Cell gyrokinetic codes for studying the effect of non-adiabatic passing electron dynamics on microturbulence"*

**D.V. Mironov**, Moscow Inst. of Physics and Technology & Kurchatov Inst., RU, *"Sideways forces due to coupled kink modes in tokamaks"*

**Dr. J. Faustin**, SPC-EPFL, *"Self-consistent interaction of fast particles and ICRF waves in 3D applications of fusion plasma devices"*

**J. Rodrigues**, Univ. of Coimbra, Portugal, *"A DAQ system for an Anger scintillation camera with silicon photomultiplier"*

**A. Calado Coroado**, Instituto Superior Técnico, Lisbon, Portugal, *"Analytical Studies of Energetic Particle Resonances in Tokamaks"*

## ***APPENDIX C External activities of SPC Staff during 2016***

### ***C.1 National and international committees and ad-hoc groups***

S. Alberti	RF Power in Plasmas Conference 2017, Programme Committee Member
S. Brunner	SPS Committee
P. Bruzzone	Int. Magnet Technology Conference Organizing Committee, member Magnet Technology Advisory Board, Chairman (US) 25th Magnet Technology Conference, Programme Committee member EUCAS 2017 Conference, Programme Committee Chairman HTS for fusion ad-hoc group, member NAFASSY (Salerno) Commissione Tecnico Scientifica, member Future Fusion Magnet Assessment Group, member
B.P. Duval	EPS Board ITPA Transport and Confinement Topical Group
A. Fasoli	Eurofusion General Assembly Governing Board of F4E International Tokamak Physics Activities: Energetic Particles Topical Group Chair of Fusernet Academic Council Chair of International Scientific Council of PLAS@PAR, Paris, France Co-chair of Scientific Board of the Helmutz Virtual Institute on Advanced Microwave Diagnostics Euratom Programme Committee IEA Fusion Power Coordinating Committee Scientific Committee of the IAEA Technical Meeting on Energetic Particles Euratom – India Coordinating Committee Steering Committee of Swiss Industrial Liaison Office Project Board of EUROfusion Heating and Current Drive WPHCD Project Board of EUROfusion WPMAG Chair of Steering Committee of ECRH Upper Launcher Consortium (ECHUL) Steering Committee of European Gyrotron Consortium (EGYC)
J.P. Graves	EUROfusion Scientific and Technical Advisory Committee (STAC) Committee for international workshop on Stochasticity in Fusion Plasmas
Y.R. Martin	Project Boards of EUROfusion: DTT1, DTT2, JET2, JET4, PFC Nuklearforum Vorstand
O. Sauter	International Tokamak Physics Activities: MHD, Disruption and Control Topical Group Co-chair Varenna-Lausanne International Theory Conference
K. Sedlak	Future Fusion Magnet Assessment Group, member
D. Testa	Expert panel member of PDR got ITER HF system magnetics + Plasma Control working group Working group on the internationalisation of JET
M.Q. Tran	World Cultural Council (Interdisciplinary Committee) President of the Swiss Physical Society



	Vice-Chair Commission C16 of the International Union for Pure and Applied Physics International Committee of the 2017 International Conference on Fusion Reactor Materials ESFRI SWG on Energy Committee Physics and Engineering of the Academia Europea
L. Villard	Board of the High Performance Computing for Fusion, Eurofusion Standing Committee of the IFERC CSC, Japan Scientific Advisory Committee (Fachbeirat), Max-Planck-Institut für Plasmaphysik, Garching and Greifswald Board of the High Level Support Team, Eurofusion Scientific Committee of the Energy-oriented Centre of Excellence, EoCoE (22 institutions from 8 countries) Co-Chair, PASC16 Conference, Platform for Advanced Scientific Computing
P. Ricci	Marconi Fusion Allocation committee, Eurofusion Organising Committee, Int. Conference on Numerical Simulation of Plasmas
H. Weisen	Seconded to EFDA-JET CSU, programme department

## ***C.2 Editorial and society boards***

S. Alberti	Editorial Board International Journal Infrared Millimeter and Terahertz Waves
A. Fasoli	Editor in Chief of Nuclear Fusion
J.P. Graves	Editorial Board of Plasma Physics and Controlled Fusion
Y.R. Martin	Board of FuseCOM, the EUROfusion communication Network Board and committee of the Société Vaudoise des Sciences Naturelles Chairman of the Association Vaudoise des Chercheurs en Physique
P. Ricci	Associate Editor of Journal of Plasma Physics Editorial Board of Plasma Physics and Controlled Fusion

## ***C.3 EPFL committees and commissions***

A. Fasoli	Comité Exécutif de l'Institut de Physique, EPFL
J.P. Graves	Commission du Doctorat de la Section de Physique, FSB-EPFL
J-Ph. Hogge	Commission du Doctorat de la Section de Physique, FSB-EPFL Conseil de l'IPHYS - Représentant du corps intermédiaire
P. Ricci	Groupe de travail technique HPC (High Performance Computing) – EPFL Commission du Doctorat de la Section de Physique, FSB-EPFL
M.Q. Tran	Commission du Doctorat de la Section de Physique, FSB-EPFL Membre du Comité de Sélection du Prix de la meilleure thèse EPFL "Core Group" of the Master in Nuclear Engineering Programme
L. Villard	Délégué à la mobilité, Section de physique, FSB-EPFL Commission d'Ethique, EPFL Commission d'Enseignement de la Section de Physique, FSB-EPFL

Steering Committee, HPC (High Performance Computing) – EPFL  
Academic Promotion Committee, FSB-EPFL

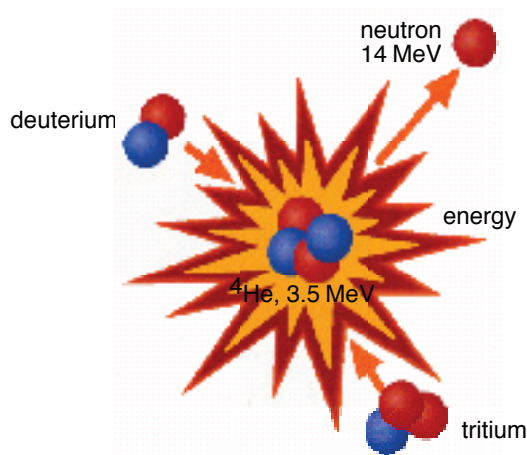
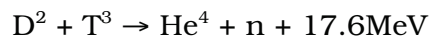
***C.4 EUROfusion Task Force leaders and Project Leaders***

S. Coda	WPMST1: Medium-Size Tokamak Campaigns, Deputy Task Force Leader deputy
H. Reimerdes	WPDTT1: Assessment of Alternative Divertor Geometries and Liquid Metals PFCs, Project Leader
M.Q. Tran	WPHCD: H&CD systems, Project Leader
H. Weisen	WPJET1: JET Campaigns - Physics and technology for ITER, Deputy Task Force Leader

## ***APPENDIX D The basis of controlled fusion***

### ***D.1 Fusion as a sustainable energy source***

Research into controlled fusion aims at demonstrating that fusion is a valid option for generating power in the long term future in an environmentally, politically and economically acceptable way. Controlled fusion is a process in which light nuclei fuse together to form heavier ones. During this process a very large amount of energy is released. For a fusion reactor it is planned to use the two isotopes of hydrogen: deuterium (D) and tritium (T), which fuse together much more readily than any other combination of light nuclei according to the following reaction:

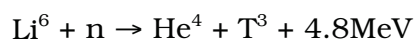


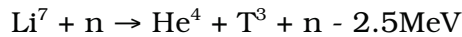
***Fig. D.1***      *Schematic of a fusion reaction between deuterium and tritium nuclei. The products are 3.5MeV  $^4\text{He}$ , the common isotope of helium, and a 14MeV free neutron.*

The end products are helium and neutrons (n). The total energy liberated by fusing one gram of a 50:50 mixture of deuterium and tritium is 94000kWh, which is 10 million times more than from the same mass of oil. 80% of this energy is carried by the neutron with an energy of 14MeV while the remaining 20% is carried by the helium nucleus. Most of this energy eventually becomes heat to be stored or converted by conventional means into electricity.

The temperature at which fusion reactivity starts to become significant are above a few tens of millions of degrees. For the D-T reaction, the optimal temperature range is of 70-200 million degrees. At such temperatures the D-T fuel is in the plasma state.

Deuterium is very abundant on the earth and can be extracted from water (0.034g/l). Tritium does not occur naturally, since its half-life is only 12.3 years, but it can be generated from lithium using the neutrons produced by the D-T fusion reactions. The two isotopes of natural lithium contribute to this breeding of tritium according to the reactions:





The relative abundance of the two lithium isotopes  $\text{Li}^6$  and  $\text{Li}^7$  are 7.4% and 92.6%, respectively. The known geological resources of lithium both in the earth and in the sea water are large enough to provide energy for an essentially unlimited time.

## ***D.2      Attractiveness of fusion as an energy source***

The inherent advantages of fusion as an energy source are:

- The fuels are plentiful and their costs are negligible because of the enormous energy yield of the reaction;
- The end product of the reaction is helium, an inert, non-radioactive gas;
- No chain reaction is possible;
- Only a very small amount of fuel is present in the core of the reactor;
- Any malfunction would cause a quick drop of temperature and all fusion reactions would stop within seconds;
- No after-heat problem can lead to thermal runaway even in the case of a loss of coolant accident;
- None of the materials required by a fusion power plant are subject to the provisions of the non-proliferation treaties.

Further potential advantages are:

- Radioactivity of the reactor structure, caused by neutrons, can be minimised by careful selection of low-activation materials resulting in a manageable quantity of long lived radioactive waste;
- The release of tritium in normal operation can be kept at a very low level. The inventory of tritium on the site can be sufficiently small so that even the worst possible accident could not lead to a harmful release to the environment requiring evacuation of the nearby population.

## ***APPENDIX E Sources of Financial Support***

In 2016, the work carried out at the SPC and presented in this annual report was financed from several sources, through either Research Grants and Subsidies, or Service Contracts. Direct financial support is provided by:

### Swiss public institutions:

- the Ecole Polytechnique Fédérale de Lausanne (EPFL)
- the Swiss National Science Foundation (SNSF)
- the Board of the Swiss Federal Institutes of Technology (ETH board)
- the Paul Scherrer Institute (PSI), which hosts the Superconductivity science activities
- the Swiss State Secretariat for Education, Research and Innovation (SERI)
- the Swiss Commission for Technology and Innovation (CTI)

### International public institutions:

- The eighth (Horizon 2020) and seventh Framework Programme for Research and Technological Development of the European Union, including EURATOM
- ITER
  - ITER Organization (IO), Cadarache, France
  - Domestic Agencies in China, Europe (F4E), Japan, Korea, Russia, USA
- European Organization for Nuclear Research (CERN), Geneva
- Helmholtz Association of German Research Centres (HGF), Germany
- Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Cadarache, France
- The Lawrence Livermore National Laboratory (LLNL), USA

### Private organisations

- Bruker BioSpin SA, Fällanden
- Gebert Rűf Stiftung, Basel